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In-situ Resource Utilization for the Moon, Mars and Beyond……

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September, 2011


NASA
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Stepping stone approach

Beyond 2010?

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- Shuttle retire September 2010
- Constellation cancelled?
- In the absence of manned missions, NASA plans science orbiters, rovers and landers, and possible mission to return samples of Martian rock and soil to Earth
- Technology development for advanced capabilities such as miniaturized surface science instruments and deep drilling to hundreds of meters will also be carried out in this period
- The program envisions significant international participation

Living Off the Land

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- In-Situ Resource Utilization
- Extracting resources from planetary bodies ("living off the land")
- Reduces reliance on Earth-supplied consumables
- Reduces mass launched from Earth to support a lunar outpost, increasing the payload capability for other objectives, such as science

Priorities for ISRU capabilities

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Regolith excavation and transport	For radiation/micro-meteorite shielding and thermal moderation
Water production	From regolith for life support and radiation shielding
Oxygen production	From regolith for life support and propulsion
Fuel production	From regolith for Earth return, lunar surface/orbital science expeditions, etc.
Energy production, transport, storage, and distribution	For outpost use
Structural and **building material** fabrication	For outpost use
Spare part, **machine**, and **tool** production	For outpost use
Construction and **site preparation**	Using *in-situ* materials and *in-situ* energy

ISRU cycle

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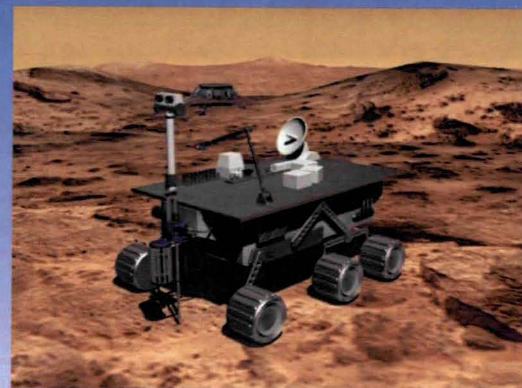
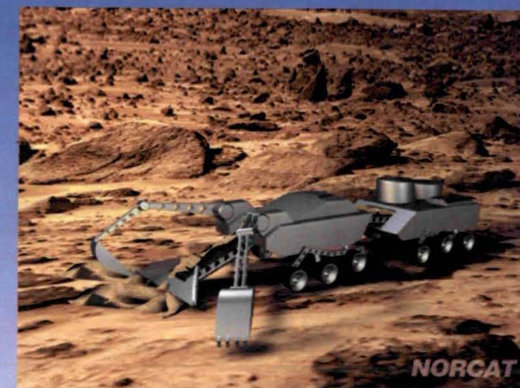
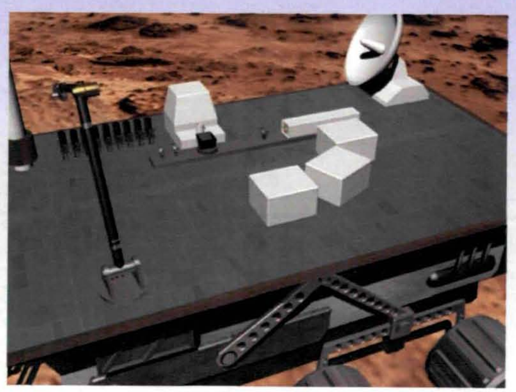
Identification

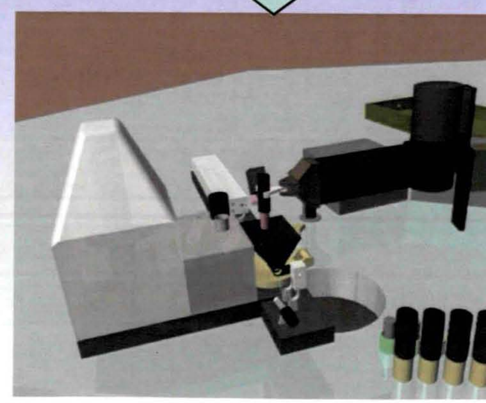
Access/Exploration



Mining







Product

Waste

Processing

Beneficiation

Beneficiation

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- Electrostatic beneficiation of lunar regolith is being investigated as part of the (ISRU) program at Kennedy Space Center
- Refinement or enrichment of specific minerals in the fine powdery regolith into an industrial feedstock before it is chemically processed would reduce the size and energy requirements to produce virgin material and reduce the process' complexity
- This would allow for more efficient extraction (e.g. oxygen) for in situ resource utilization use.

Lunar regolith

TABLE 5.1. Modal proportions (vol.%) of minerals and glasses in soils from the Apollo (*A*) and Luna (L) sampling sites (90–20 μm fraction, not including *fused*-soil and rock fragments).

	A-11	A-12	A-14	A-15 (*H*)	A-15 (M)	A-16	A-17 (H)	A-17 (M)	L-16	L-20	L-24
Plagioclase	21.4	23.2	31.8	34.1	12.9	69.1	39.3	34.1	14.2	52.1	20.9
Pyroxene	44.9	38.2	31.9	38.0	61.1	8.5	27.7	30.1	57.3	27.0	51.6
Olivine	2.1	5.4	6.7	5.9	5.3	3.9	11.6	0.2	10.0	6.6	17.5
Silica	0.7	1.1	0.7	0.9	–	0.0	0.1	–	0.0	0.5	1.7
Ilmenite	6.5	2.7	1.3	0.4	0.8	0.4	3.7	12.8	1.8	0.0	1.0
Mare Glass	16.0	15.1	2.6	15.9	6.7	0.9	9.0	17.2	5.5	0.9	3.4
Highland Glass	8.3	14.2	25.0	4.8	10.9	17.1	8.5	4.7	11.2	12.8	3.8
Others	–	–	–	–	2.3	–	–	0.7	–	–	
Total	99.9	99.9	100.0	100.0	100.0	99.9	99.9	99.8	100.0	99.9	99.9

Data from *Papike et al.* (1982), *Simon et al.* (1982), *Laul et al.* (1978a), and Papike and *Simon* (unpublished). (H) Denotes highland. (M) Denotes mare.

G.H. Heiken, D.T. Vaniman, & B.M. French, “Lunar Source book: A Users Guide to the Moon”, Cambridge University Press, 1991

Lunar Mare soil

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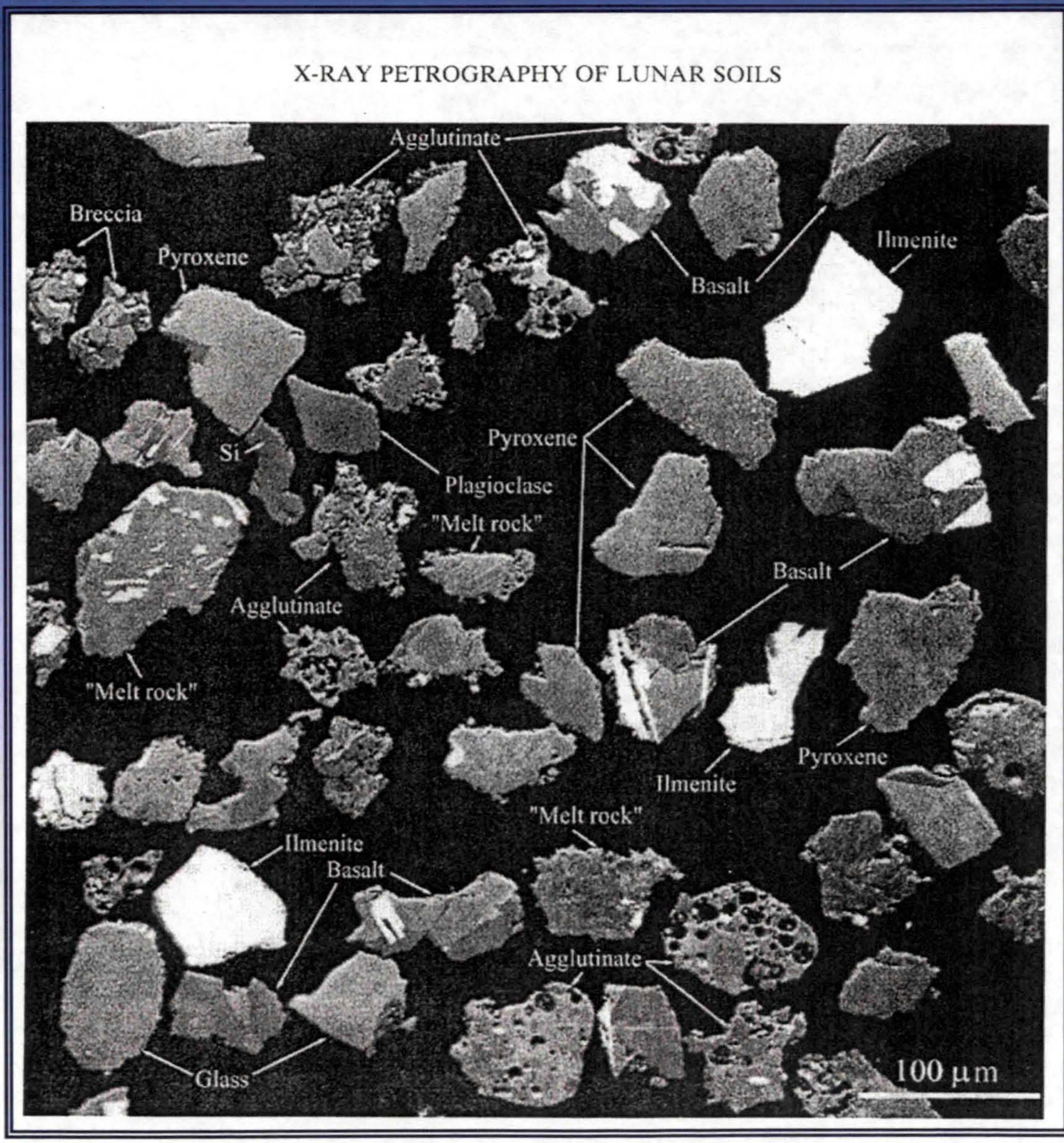

Taylor *et al.,* Icarus, 124, (1996), 500-512

Characterization

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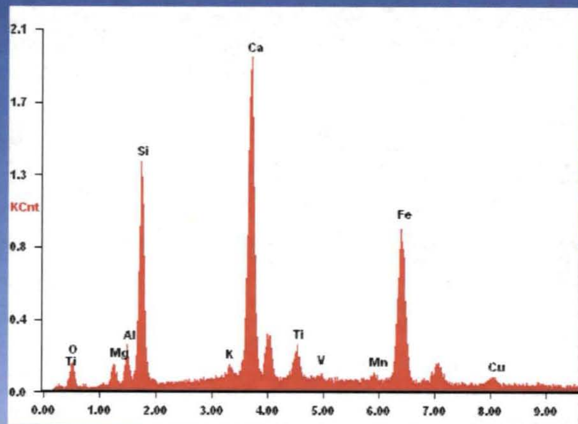
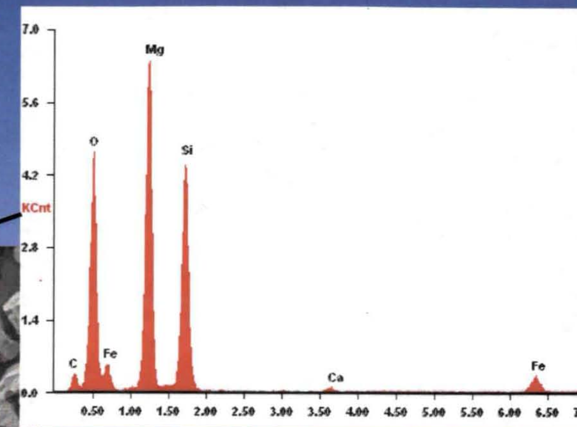
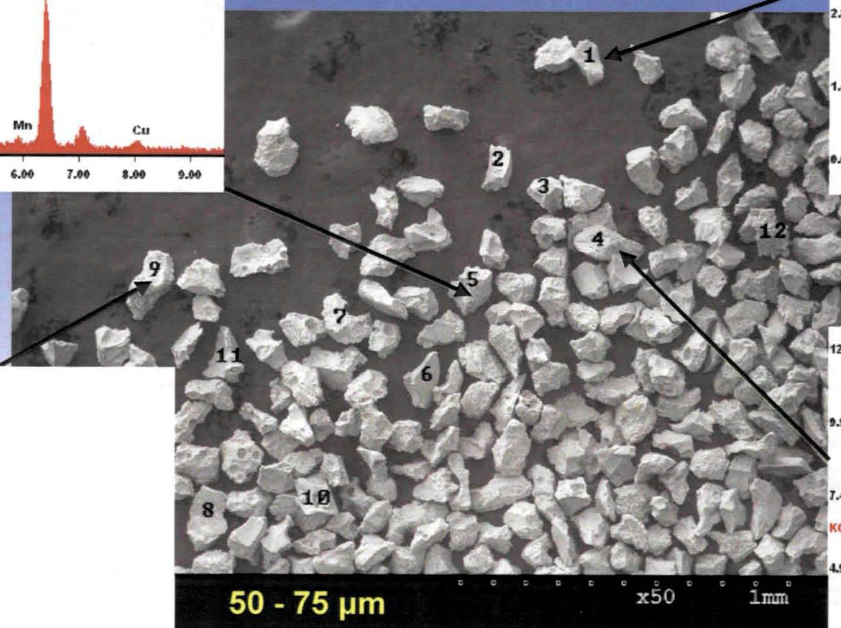
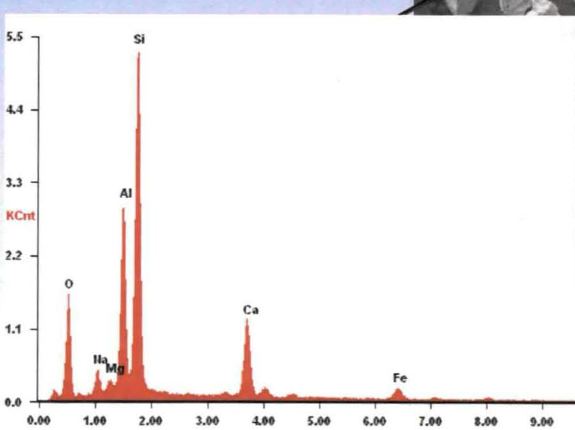
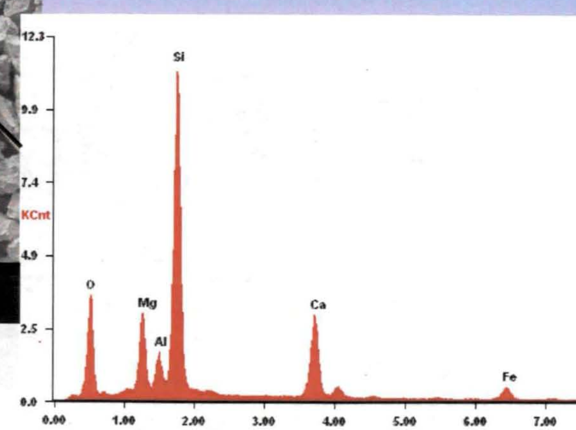
EDX of JSC-1
50 -75 µm
fraction



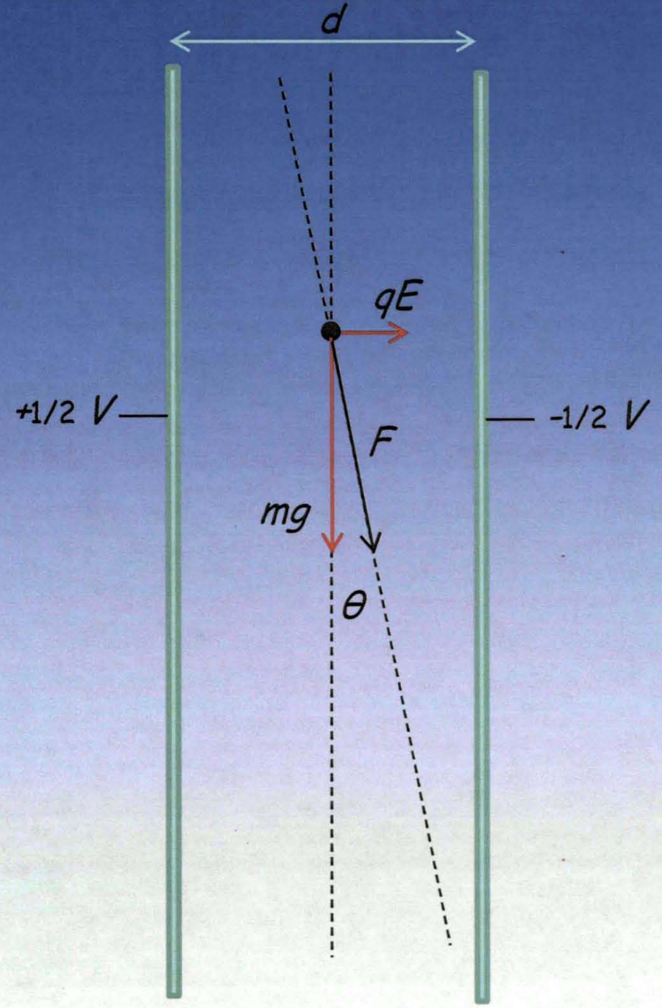




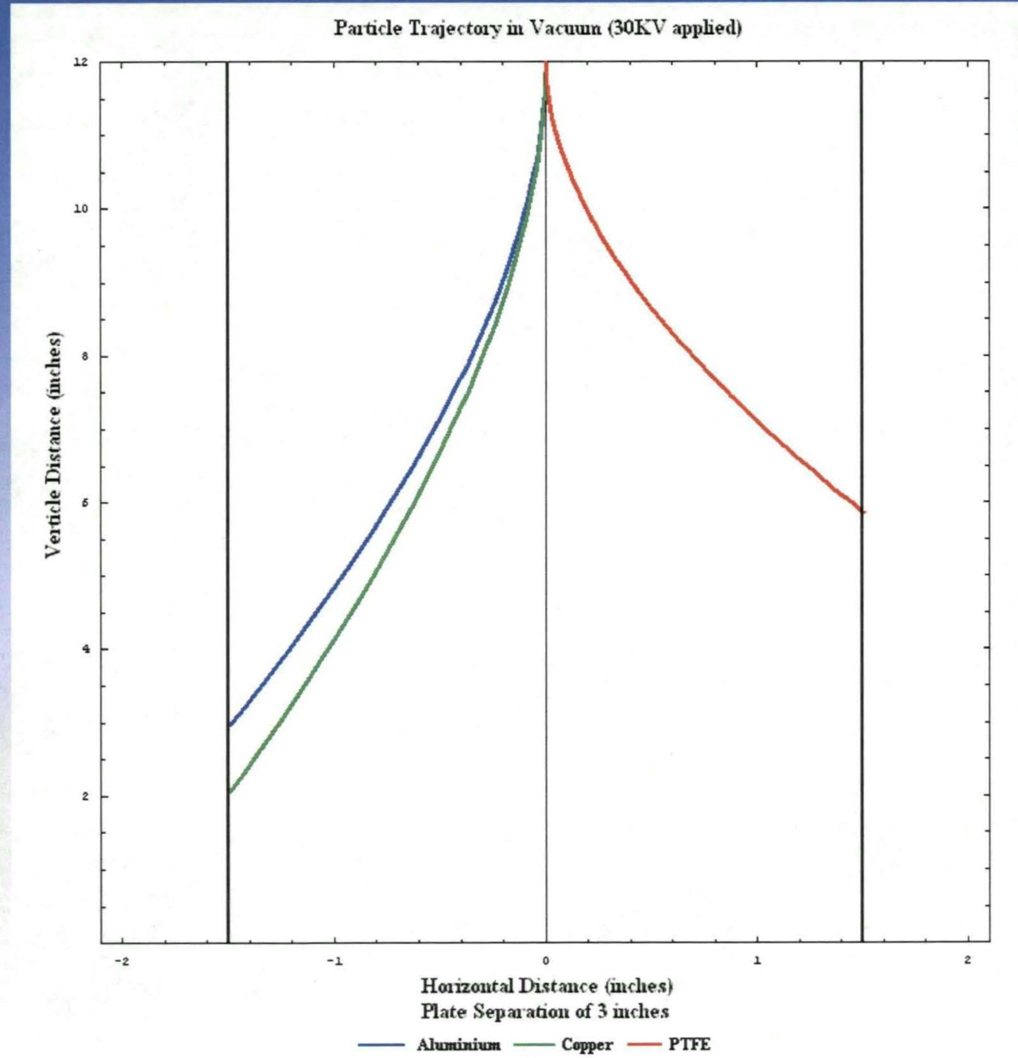




Principles of separation



$$\tan \theta = qE/mg = (q/m)((V/d)/g)$$



Principles of Tribocharging

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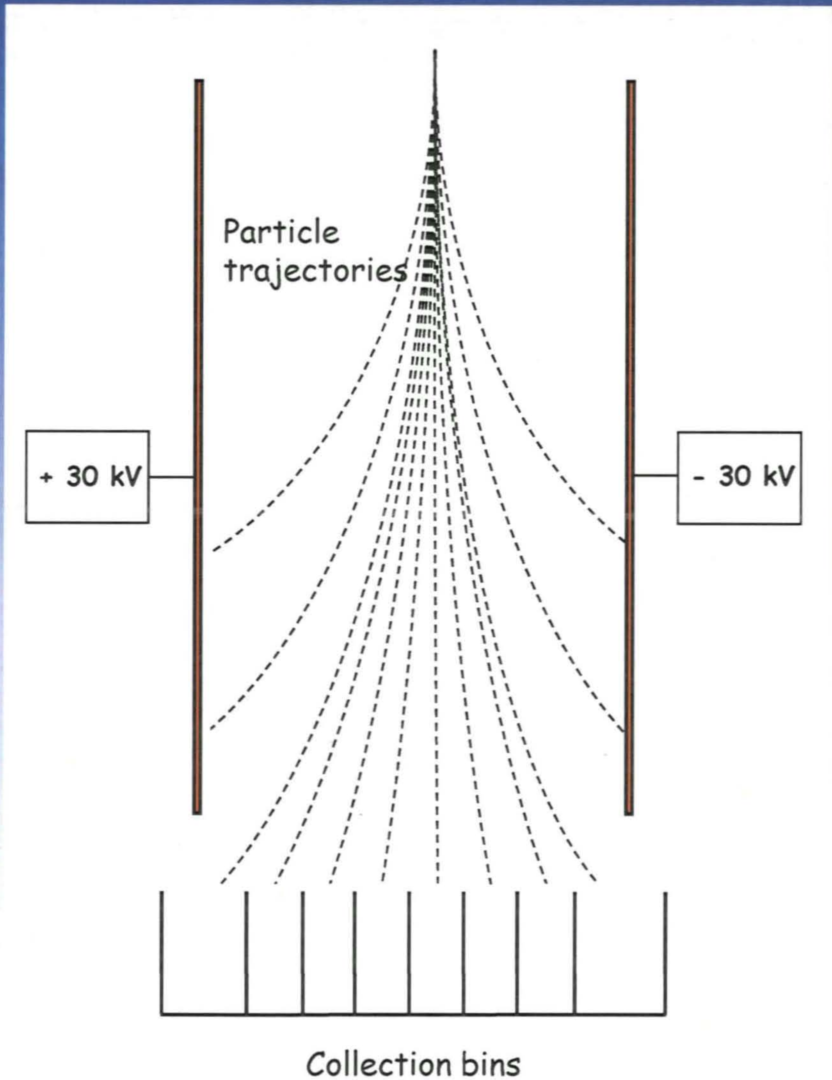

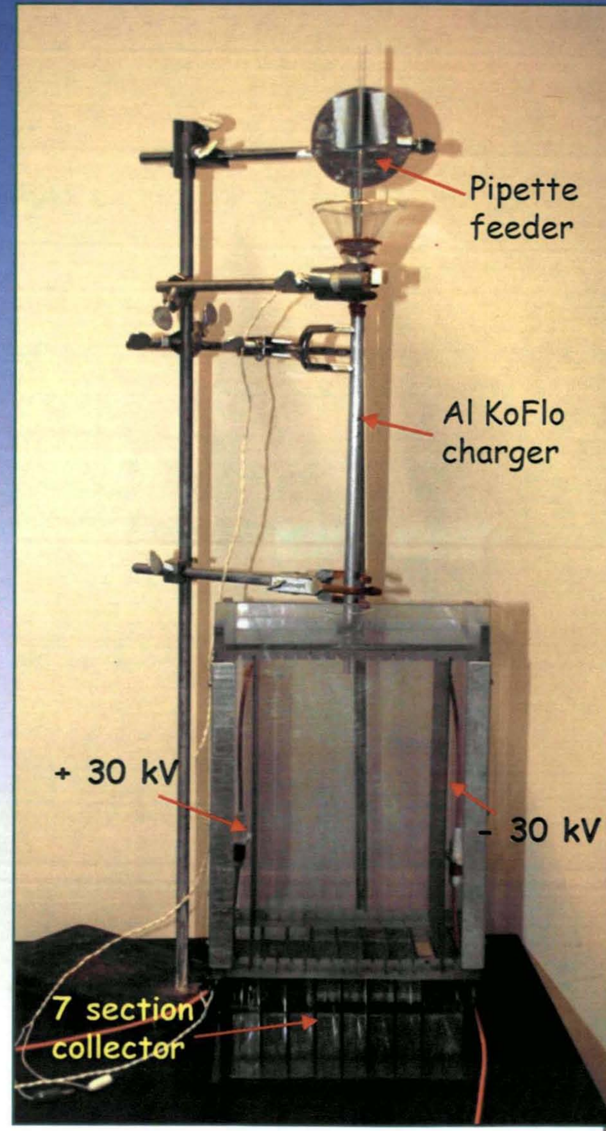

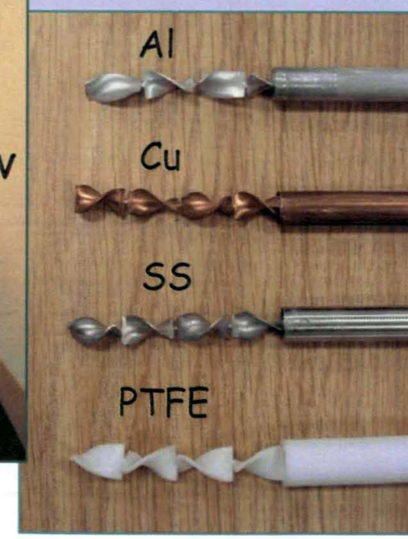

Lunar regolith

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- Lunar dust principally basalts containing
  plagioclase $(Na,Ca)Si_3AlO_8$
  pyroxene $(Mg,Fe,Ca)Si_2O6$
  olivine $(Mg,Fe)_2SiO_4$
  and ilmenite $FeTiO_3$
- Two simulants developed to replicate the mineralogy and chemistry of lunar soil from Apollo missions: NASA JSC-1 and JSC-1A

Mineral	Wt. %
Plagioclase	20 - 50
Pyroxene	40 - 65
Olivine	2 - 15
Ilmenite	2 - 15

Summary of compositions obtained from literature

- Electrostatic charging of lunar dust compared favorably to JSC-1
- Successful separation of ilmenite (up to 55%) has been reported using high-voltage electrode in N_2 environment – ilmenite favored as H_2 ore

X-ray photoelectron spectroscopy (XPS)

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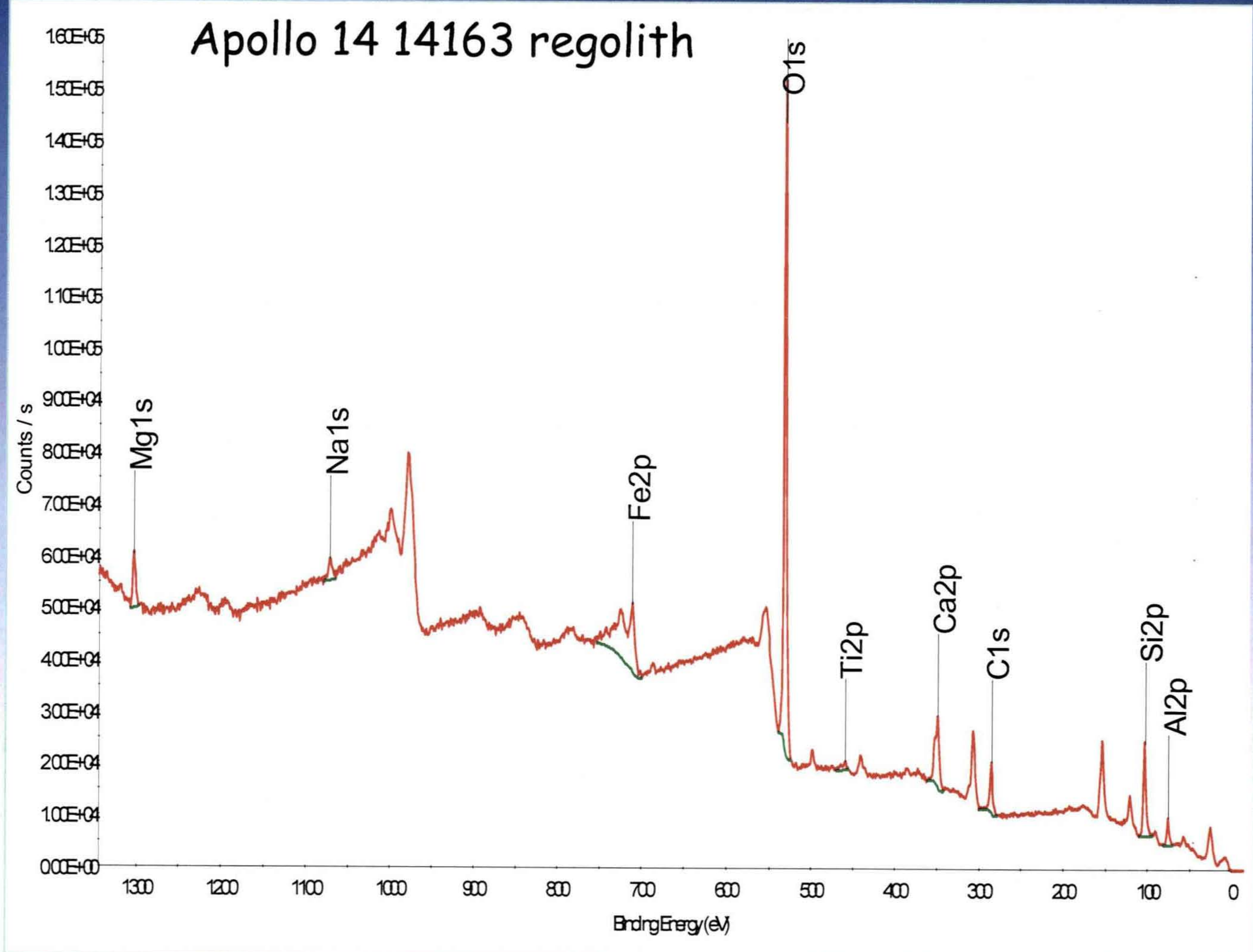

Name	Peak BE	At.%	SF
O1s	531.70	56.8	0.660
Si2p	102.86	13.6	0.270
Mg1s	1303.83	2.6	3.500
Al2p	75.08	4.7	0.185
C1s	285.0	10.4	0.250
Ca2p	348.96	3.2	1.580
Fe2p	711.46	6.9	3.000
Na1s	1071.99	1.3	2.300
Ti2p	459.31	0.4	1.800

KSC-1 1st pass

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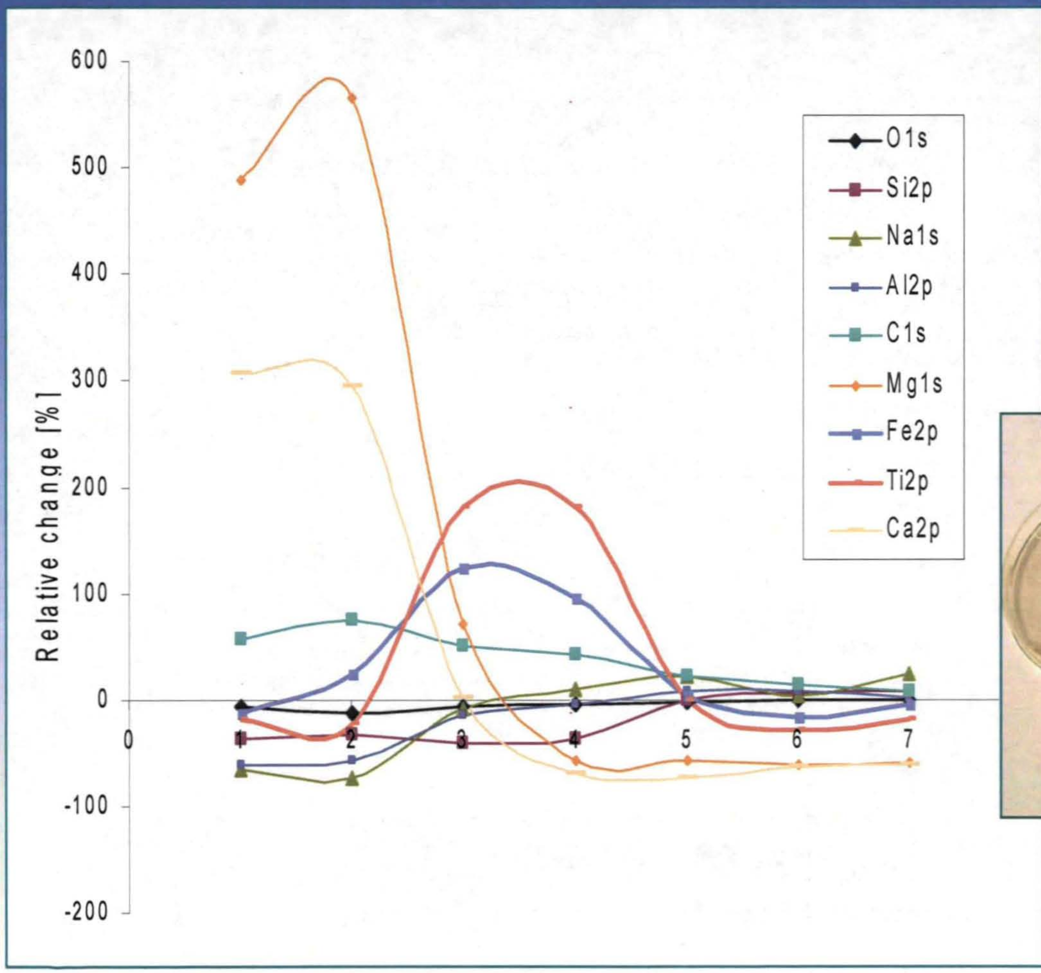

- Results from 7 tray bin
- Relative changes as determined by XPS

KSC-1 in vacuum

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KSC-1 50 - 75 μm Al charger

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-9%	-69%	-6%	-48%	+26%	+17%	+6%
-ve plate	+31%	-43%	-	-38%	+12%	+15%	-
+ve plate	-	-	-	+40%	-7%	+11%	-23%

KSC-1 50 - 75 μm Cu charger

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-10%	+11%	-	-34%	-11%	+20%	+13%
-ve plate	-7%	+86%	-	+14%	-8%	-	-8%
+ve plate	-27%	-	-	-32%	-	+11%	-

KSC-1 50 - 75 μm PTFE charger

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-	-36%	-	-31%	-10%	+23%	+18%
-ve plate	+13%	-32%	-	-26%	+9%	-	-
+ve plate	-	+27%	-	+46%	+9%	-7%	+30%

Apollo 14 14163 in vacuum

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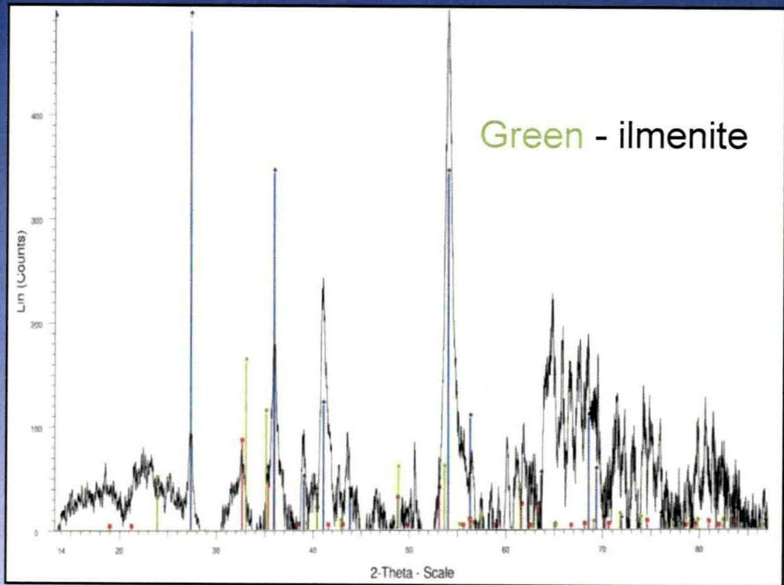
14163 Al charger

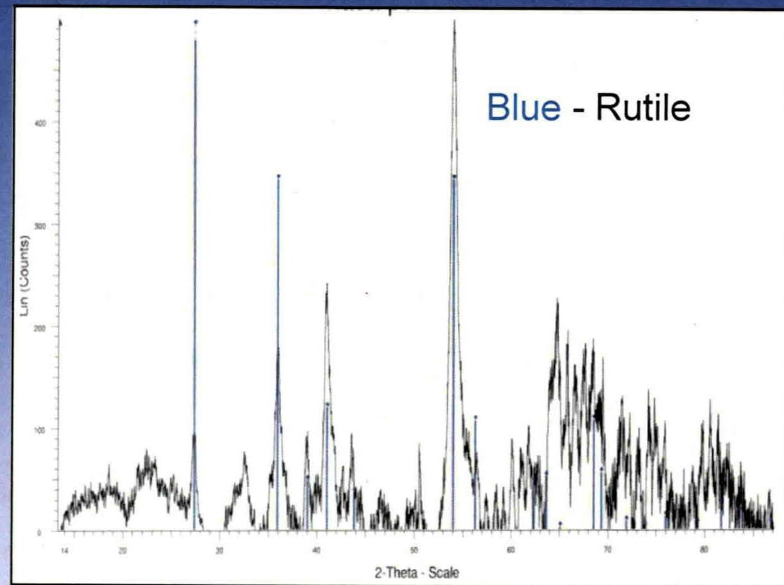
	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-	+31%	+16%	+210%	-44%	15%	+17%
-ve plate	+7%	-8%	-10%	-20%	+7%	-	-
+ve plate	+23%	+15%	+8%	+70%	-20%	+8%	-

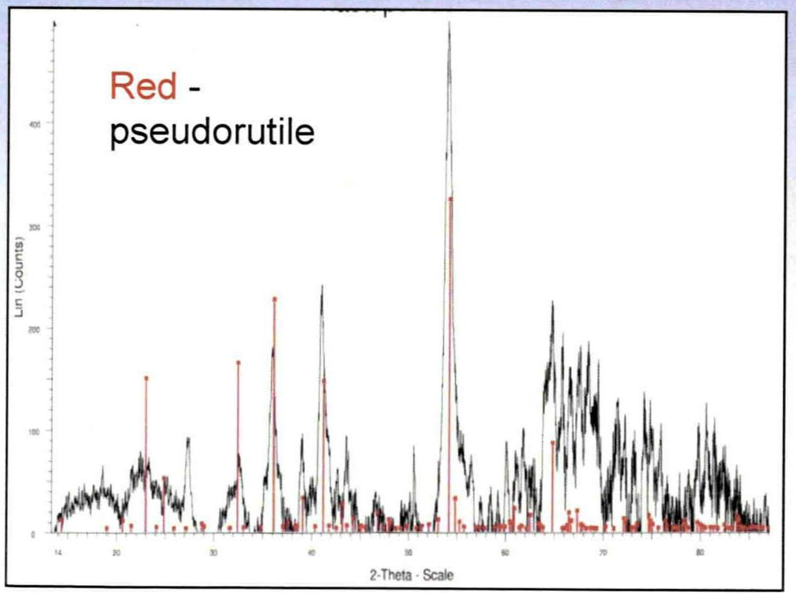
14163 PTFE charger

	Na	Fe	O	Ti	C	Si	Al
Bottom tray	-11%	+146%	+10%	-	-31%	+18%	+22%
-ve plate	-8%	+115%	-	-	-14%	+12%	+16%
+ve plate	-10%	+139%	+9%	-16%	-34%	+21%	+30%

XRD ilmenite







Common ilmenite alteration mechanism;

$$Fe^{2+}TiO_3 \rightarrow Fe_2^{3+}Ti_3O_9 \rightarrow TiO_2 + Fe_2O_3$$

Ilmenite	Pseudorutile	Rutile	Hematite

D.S. Surech Babu *et al.*, *Clays and Clay Minerals,* 42, No.5, 567-571, 1994

XPS ilmenite

XPS of Reade ilmenite (At. %) (mean of 6 samples)

C1s	Fe2p	Ti2p	O1s
12.54	9.57	17.07	60.83

Reade: $FeTi_{1.8}O_{6.4}$

Ilmenite: $FeTiO_3$

Pseudorutile: $FeTi_{1.5}O_{4.5}$

Rutile: TiO_2

Pseudo+Rutile: $FeTi_{2.5}O_{6.5}$

$$\chi_{Ti} = \frac{w_b p}{5w_b p + 3w_x(1 - p)}$$

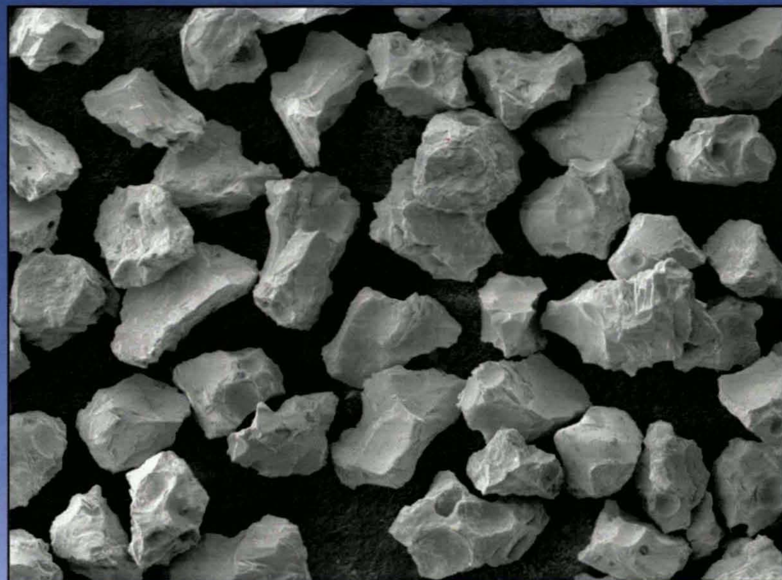
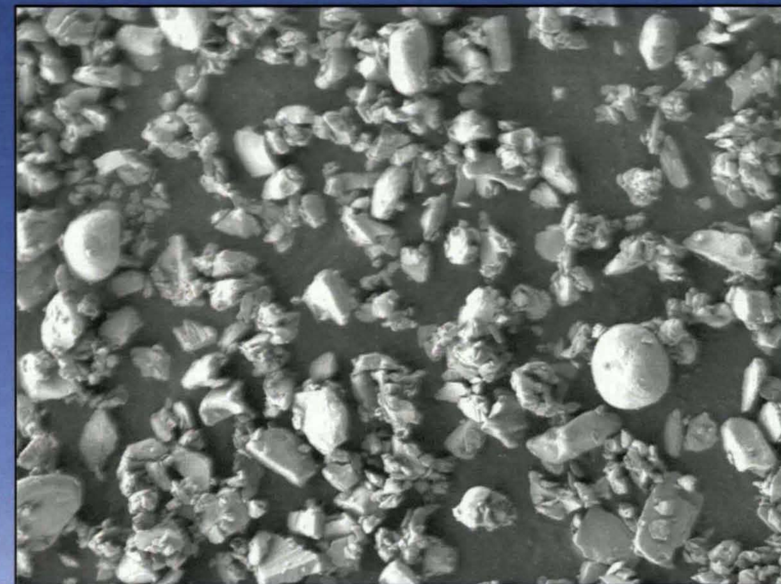
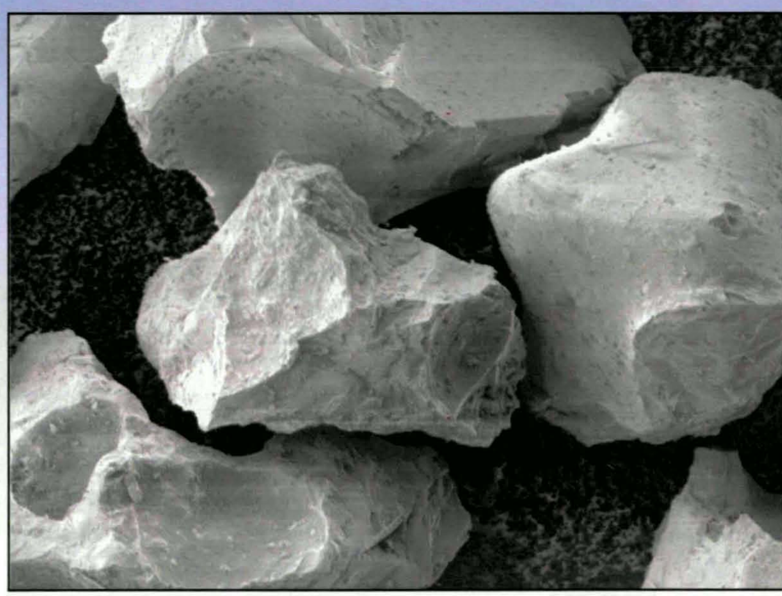
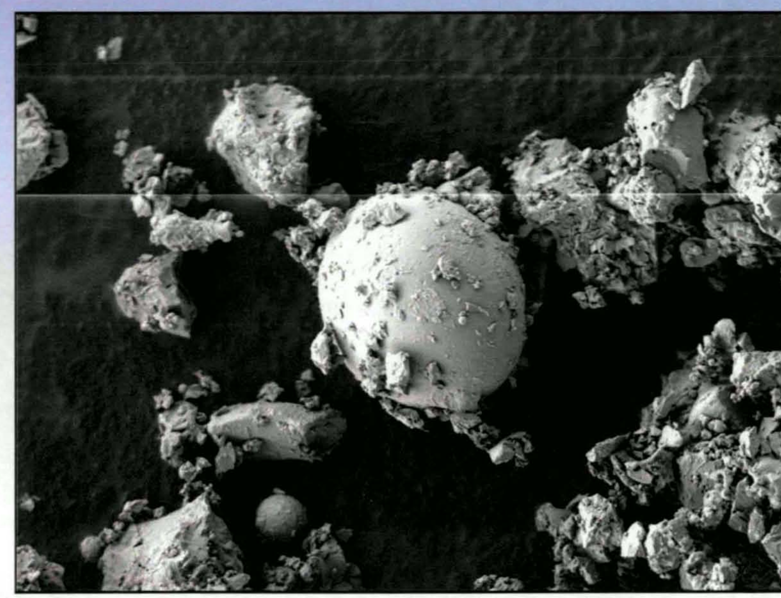
$$\chi_{Fe} = \frac{w_b p}{5w_b p + 3w_x(1 - p)}$$

$$\chi_{Si} = \frac{w_x(1 - p)}{5w_b p + 3w_x(1 - p)}$$

$$\chi_{O} = \frac{3w_b p + 2w_x(1 - p)}{5w_b p + 3w_x(1 - p)}$$

Sample Number	m_b [g] – SiO_2	m_x [g] – $FeTiO_3$	$p = \frac{m_x}{m_x + m_b}$
KSC-2a	35.4273	0.7204	0.01993
KSC-5a	35.4949	1.8712	0.05008
KSC-10a	35.4770	3.9412	0.09998
KSC-20a	34.2615	8.5886	0.2004

Sample Number	At% - *Ti*	At% - *Fe*	At% - *Si*	At% - *O*
KSC-2a	0.265	0.265	32.892	66.578
KSC-5a	0.672	0.672	32.213	66.443
KSC-10a	1.366	1.366	31.057	66.211
KSC-20a	2.839	2.839	28.602	65.721

XPS/EDS of KSC mixtures

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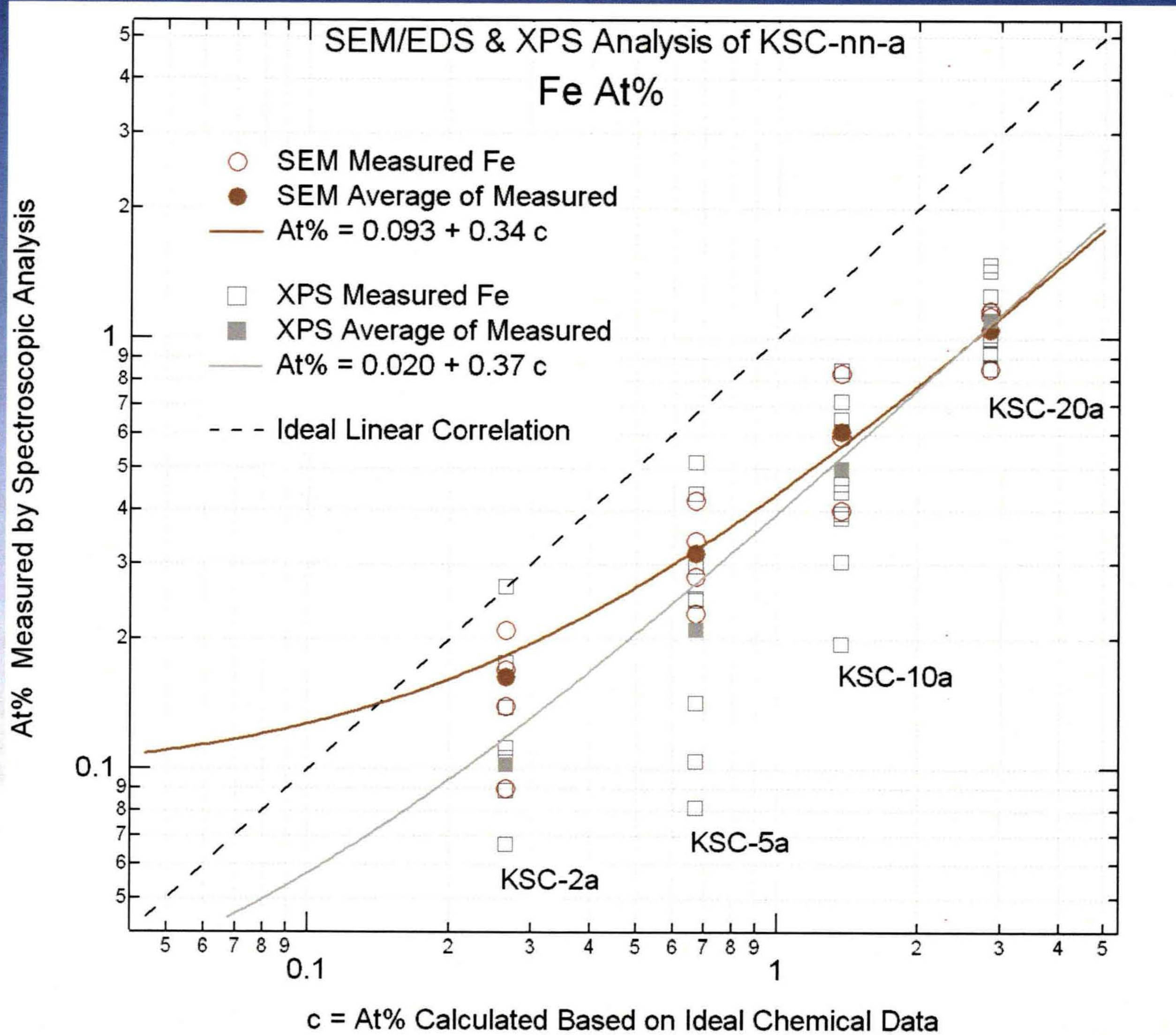

XPS/EDS of KSC mixtures

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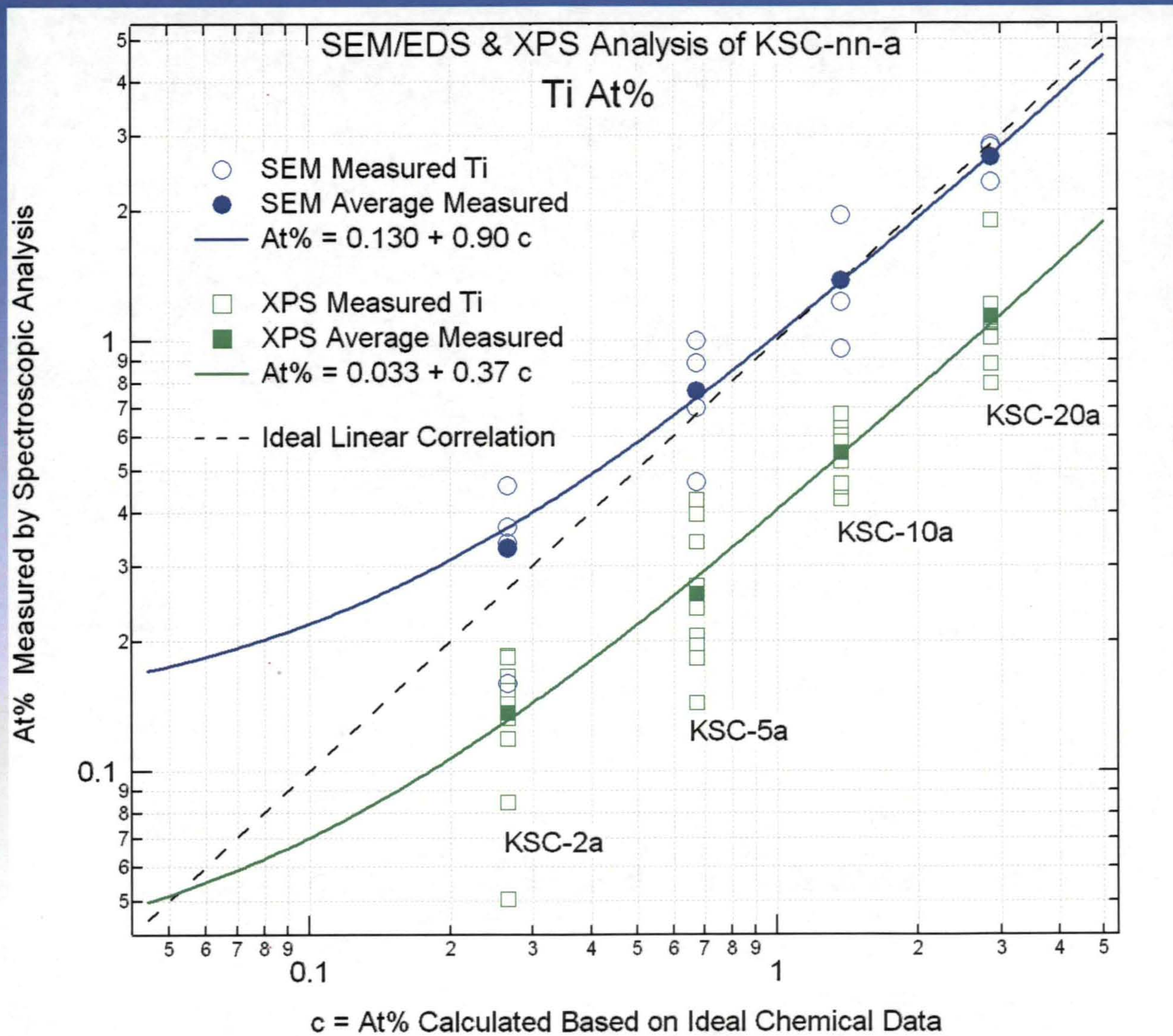

RESOLVE

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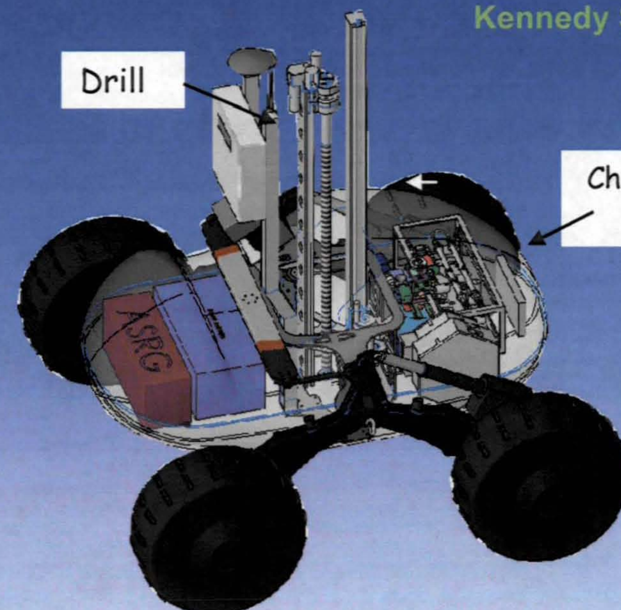
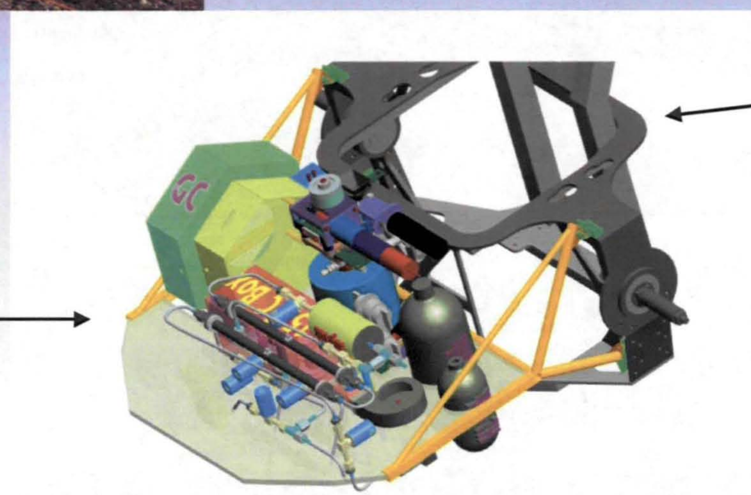
- Regolith and Environment Science & Oxygen and Lunar Volatile Extraction
- LWRD (Lunar Water Resource Demonstration) is part of RESOLVE
- RESOLVE is an ISRU ground demonstration:
  - A rover to explore a permanently shadowed crater at the south or north pole of the Moon
  - Drill core samples down to 1 meter
  - Heat the core samples to 150 °C
  - Analyze gases and capture water and/or hydrogen evolved
  - Use hydrogen reduction to extract oxygen from regolith
- The field demo took place on Mauna Kea as an analog site for the Moon
- JSC, GRC, KSC, NORCAT, CSA and CMU involved

RESOLVE/Scarab Rover





Lunar-like terrain on Mauna Kea

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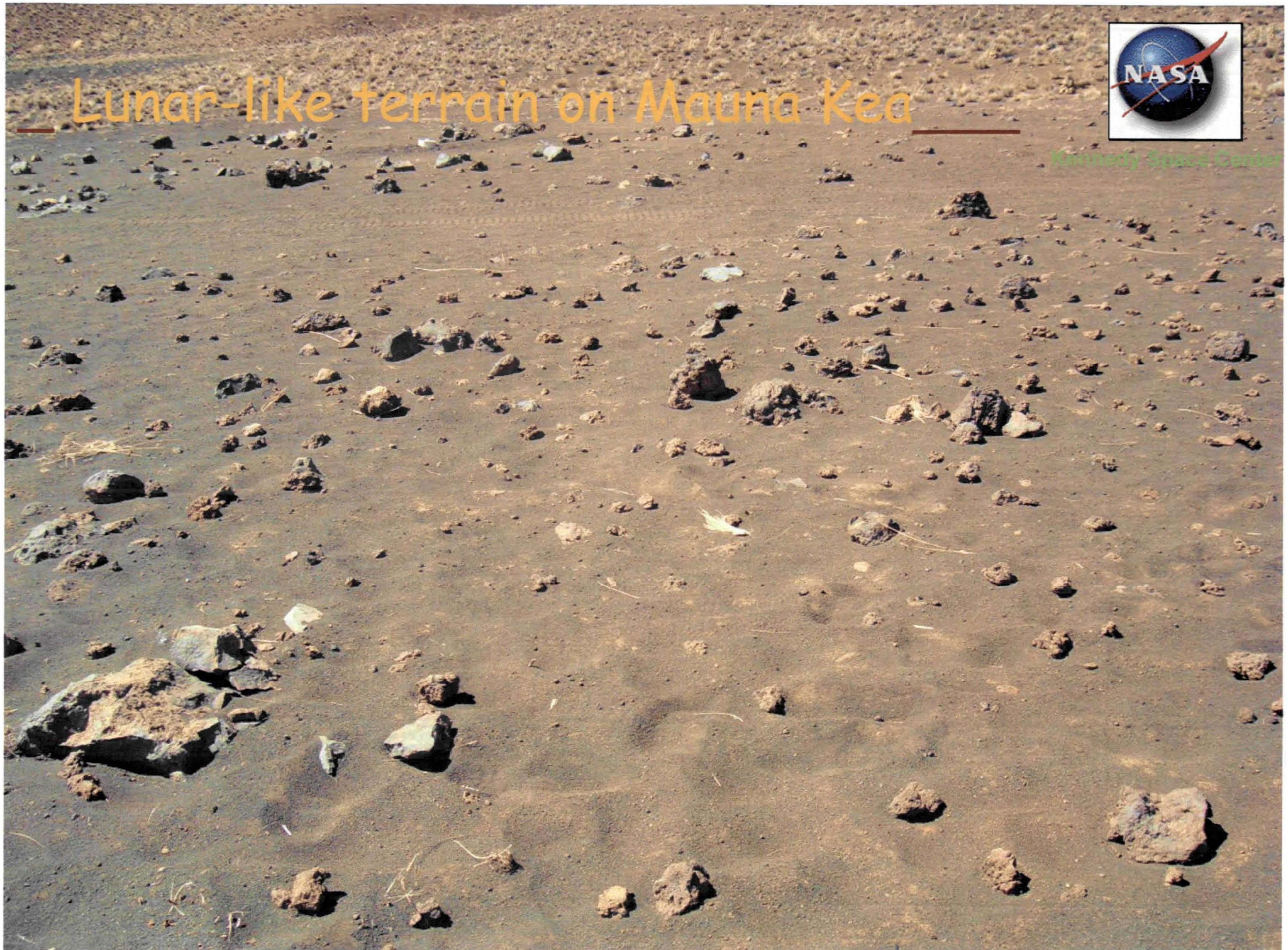

Purpose of LWRD

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- Capture up to 6 g of water per regolith/soil core sample and quantify up to 20 g of water (backup to GC measurements)
- Capture and quantify up to 0.10 g of hydrogen from same core sample (backup to GC measurements)
- Quantify within 20% accuracy

Assembly of LWRD

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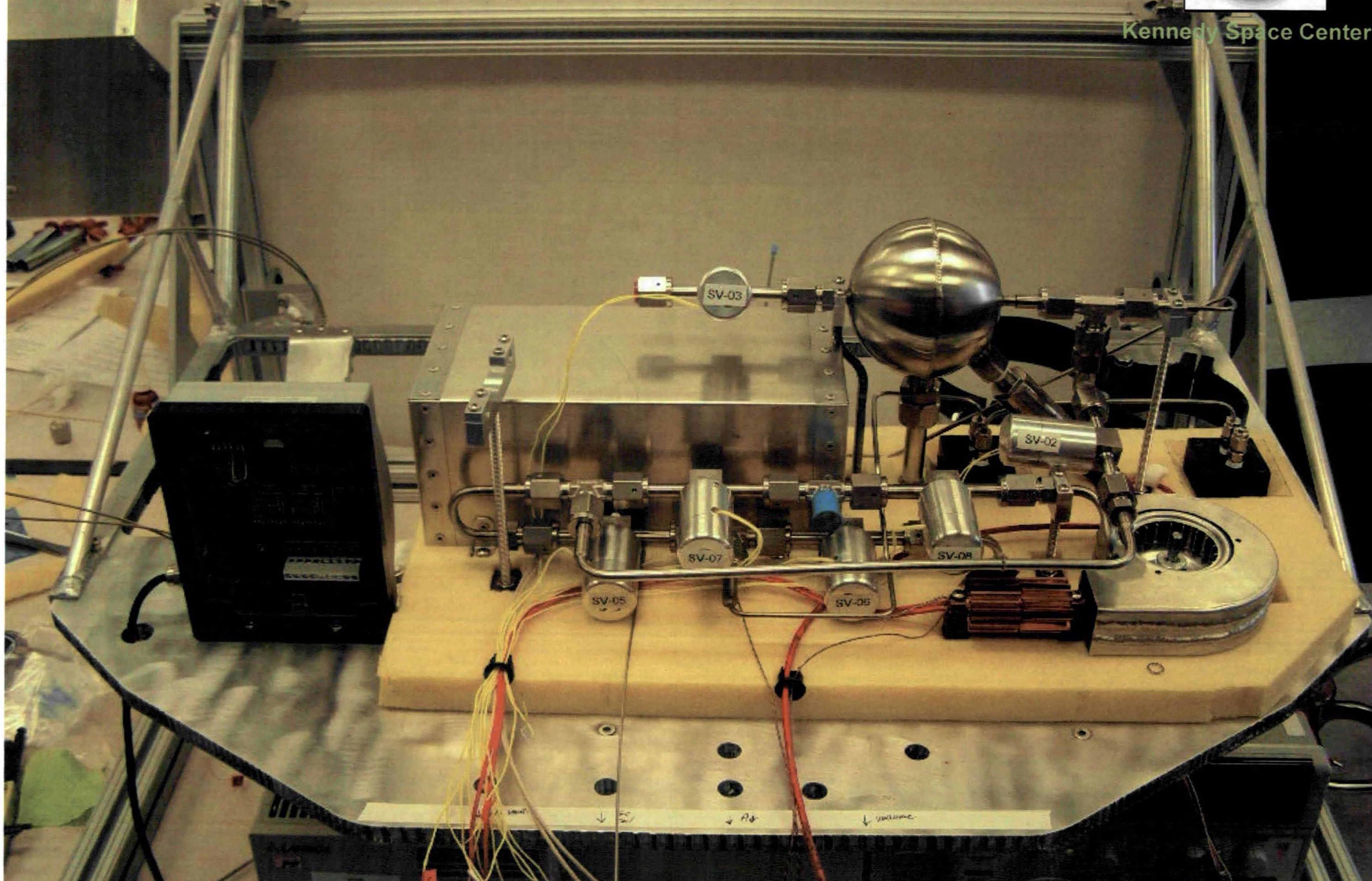

Water beds added

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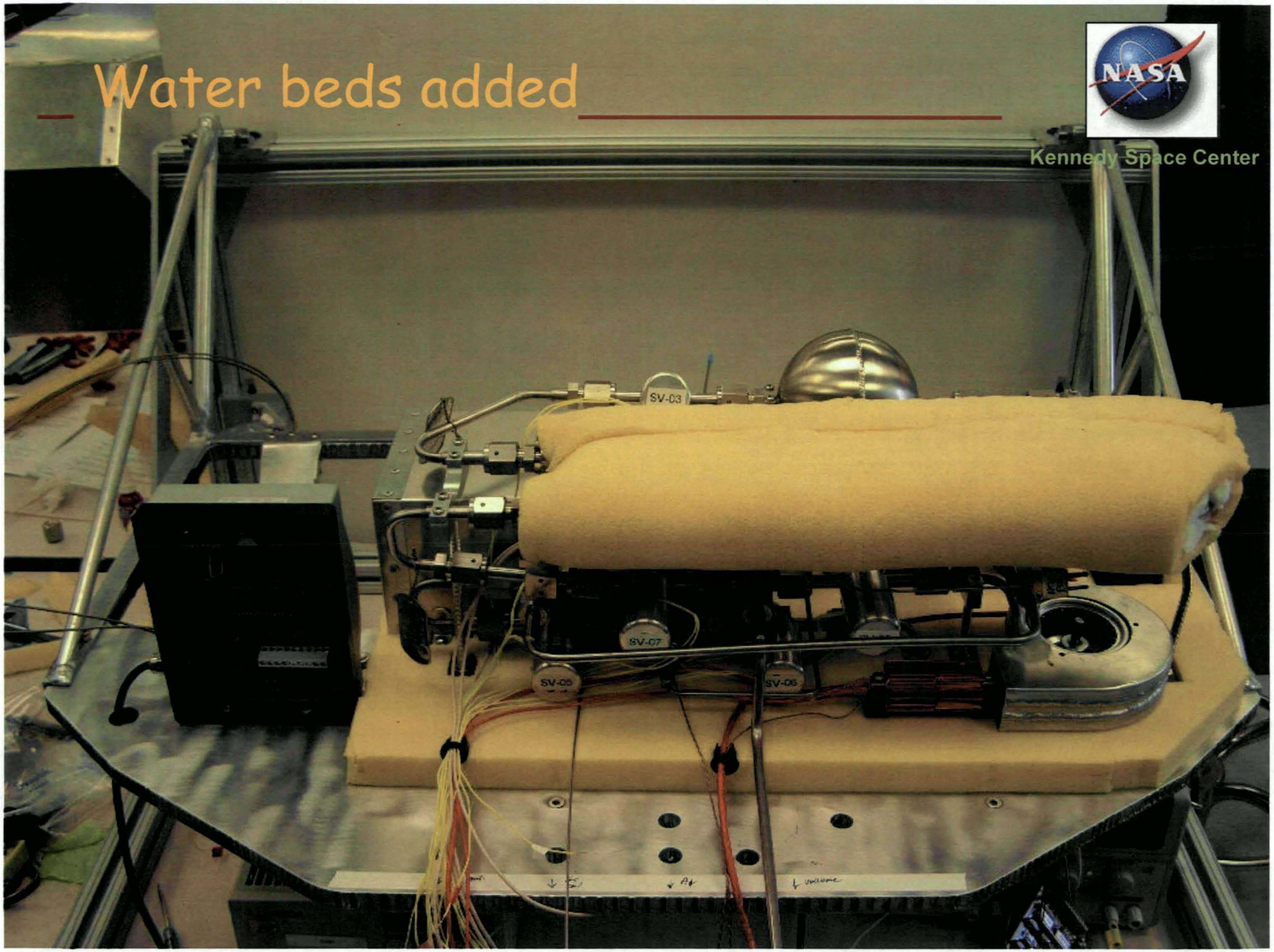

RESOLVE

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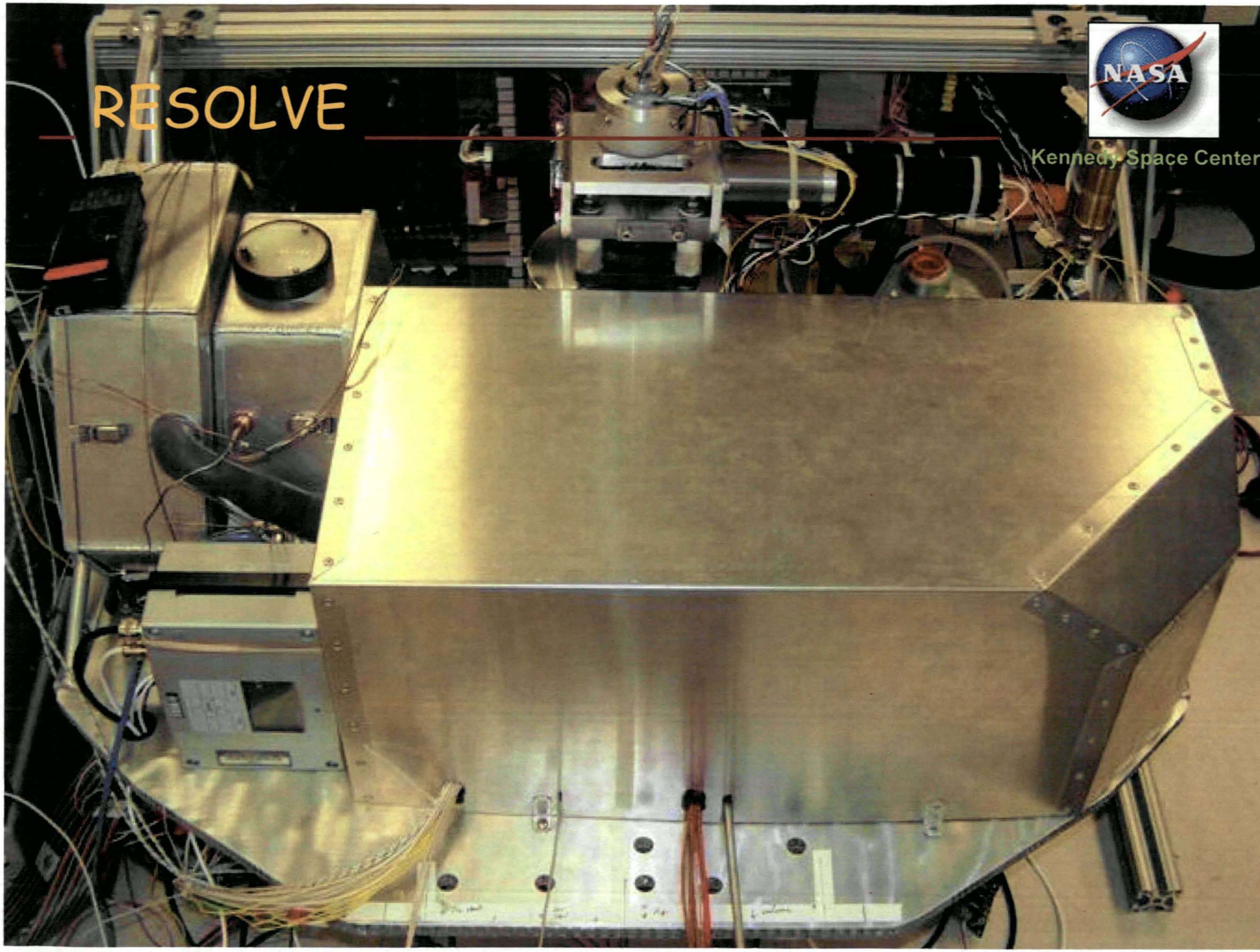

RESOLVE

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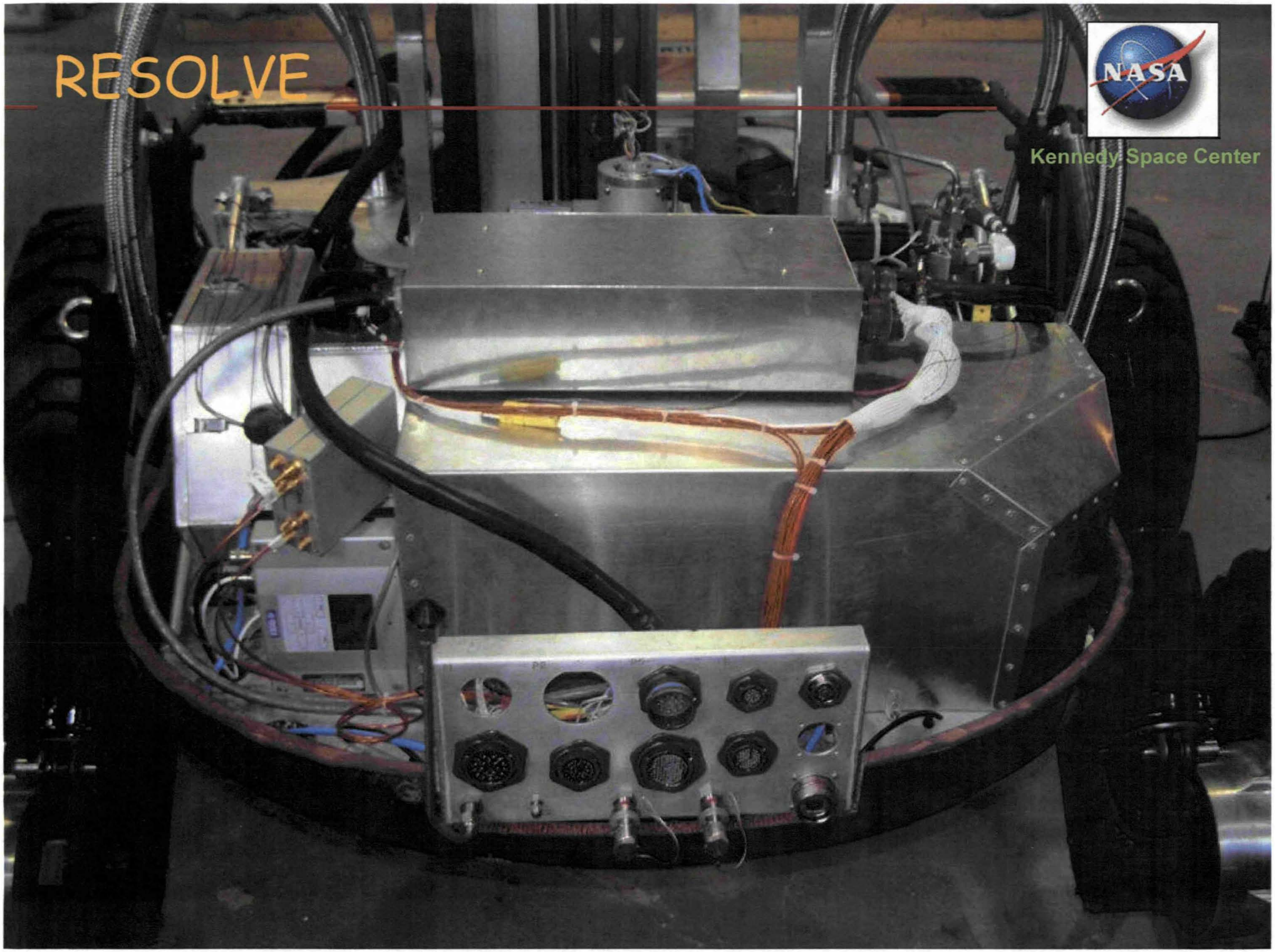

RESOLVE

RESOLVE

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RESOLVE

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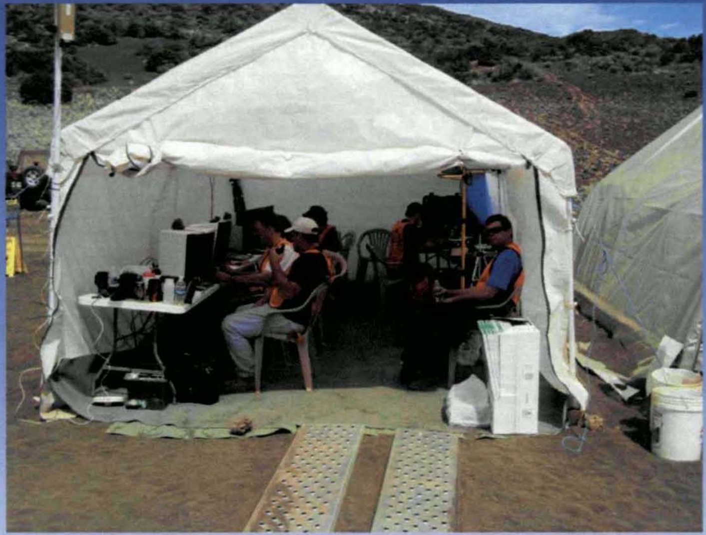
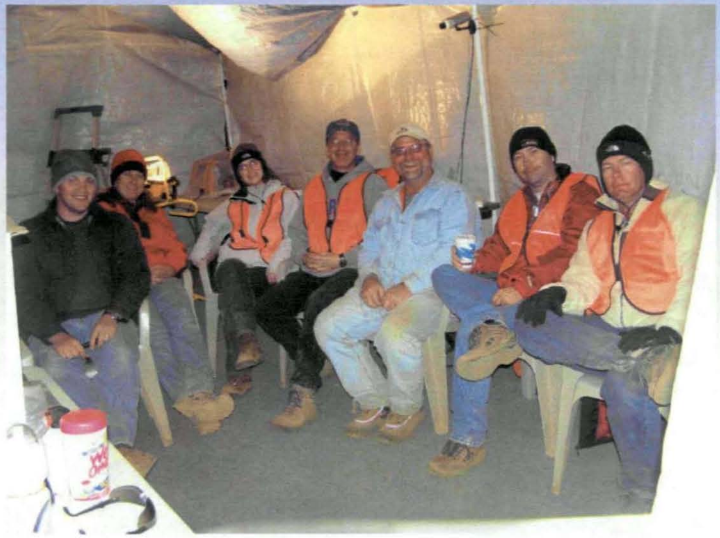
RESOLVE





RESOLVE - Overall Results

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- Remote navigation and control
- Autonomous and manual operation
- Drill site selection
- Roving
- Sample acquisition
- Volatiles characterization
- Volatiles capture

RESOLVE

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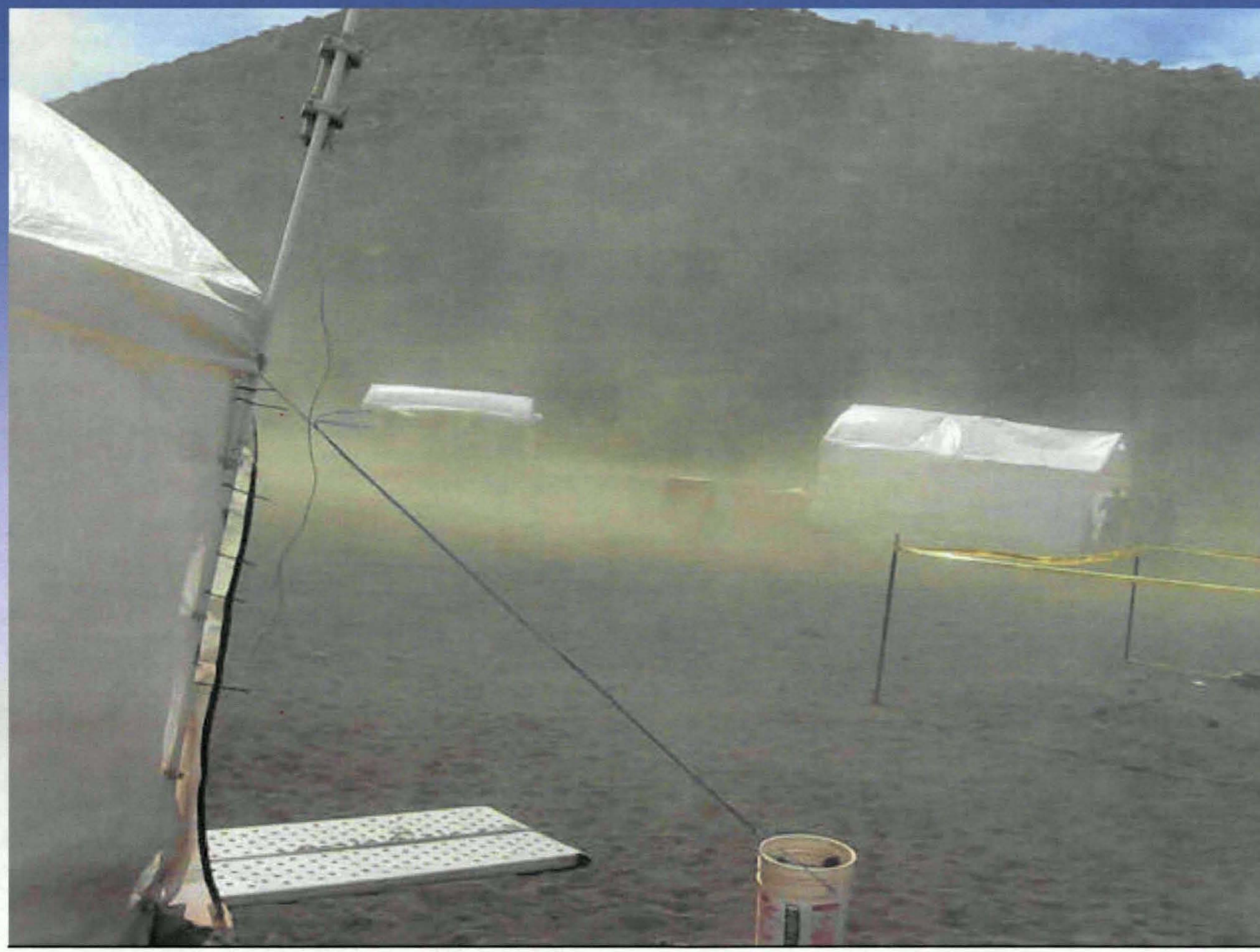

Dirt That Hurts

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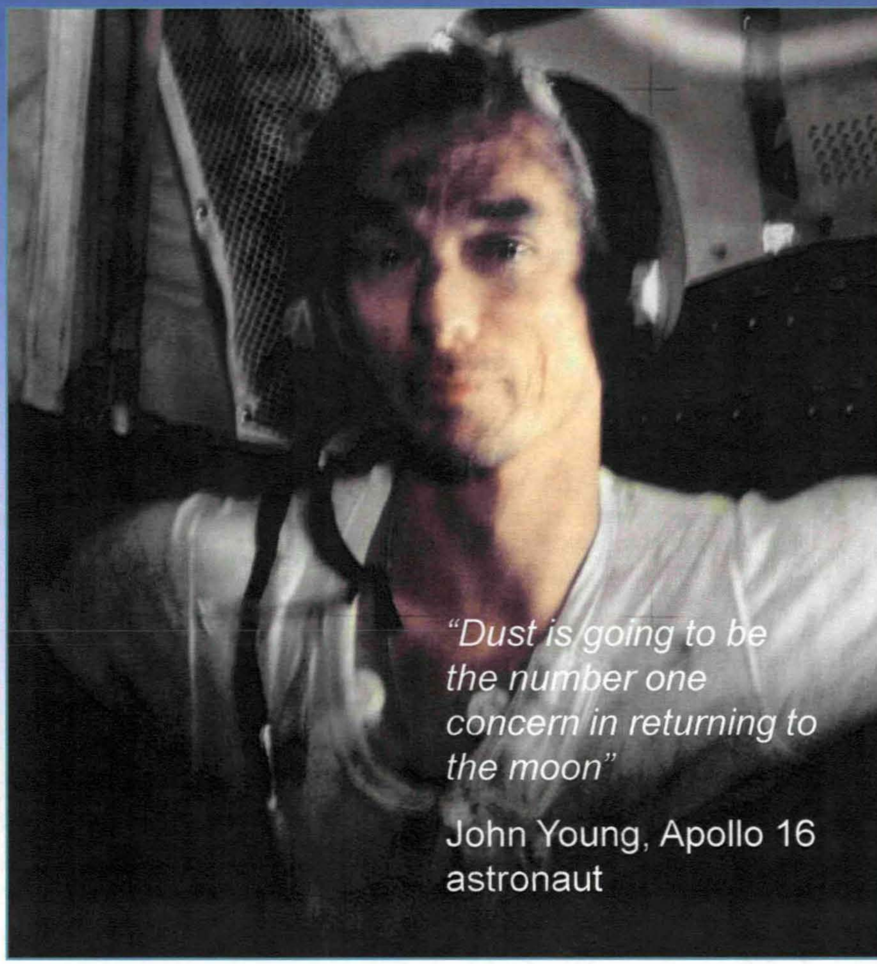

Martian Dust storms

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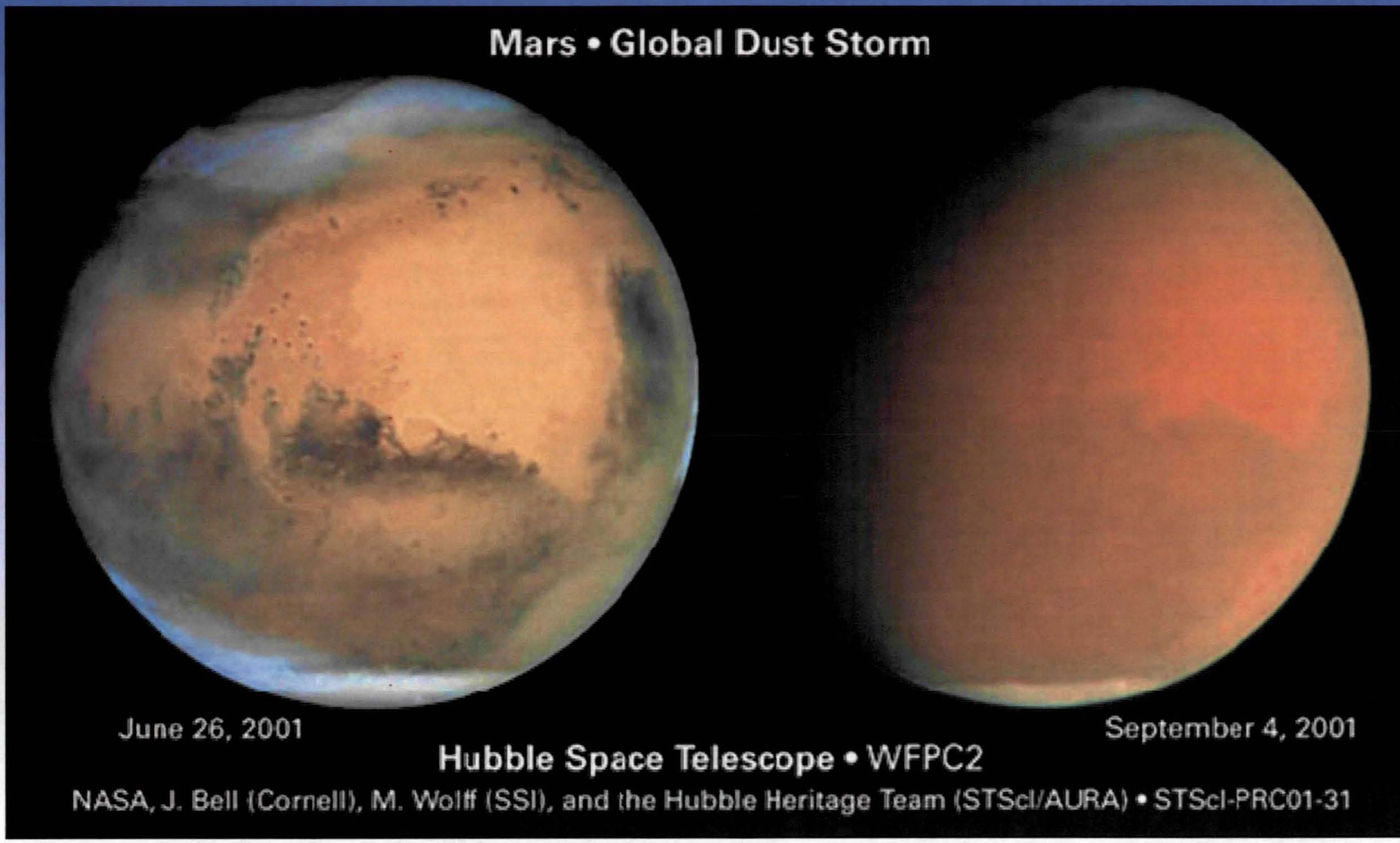

Martian Dust storms

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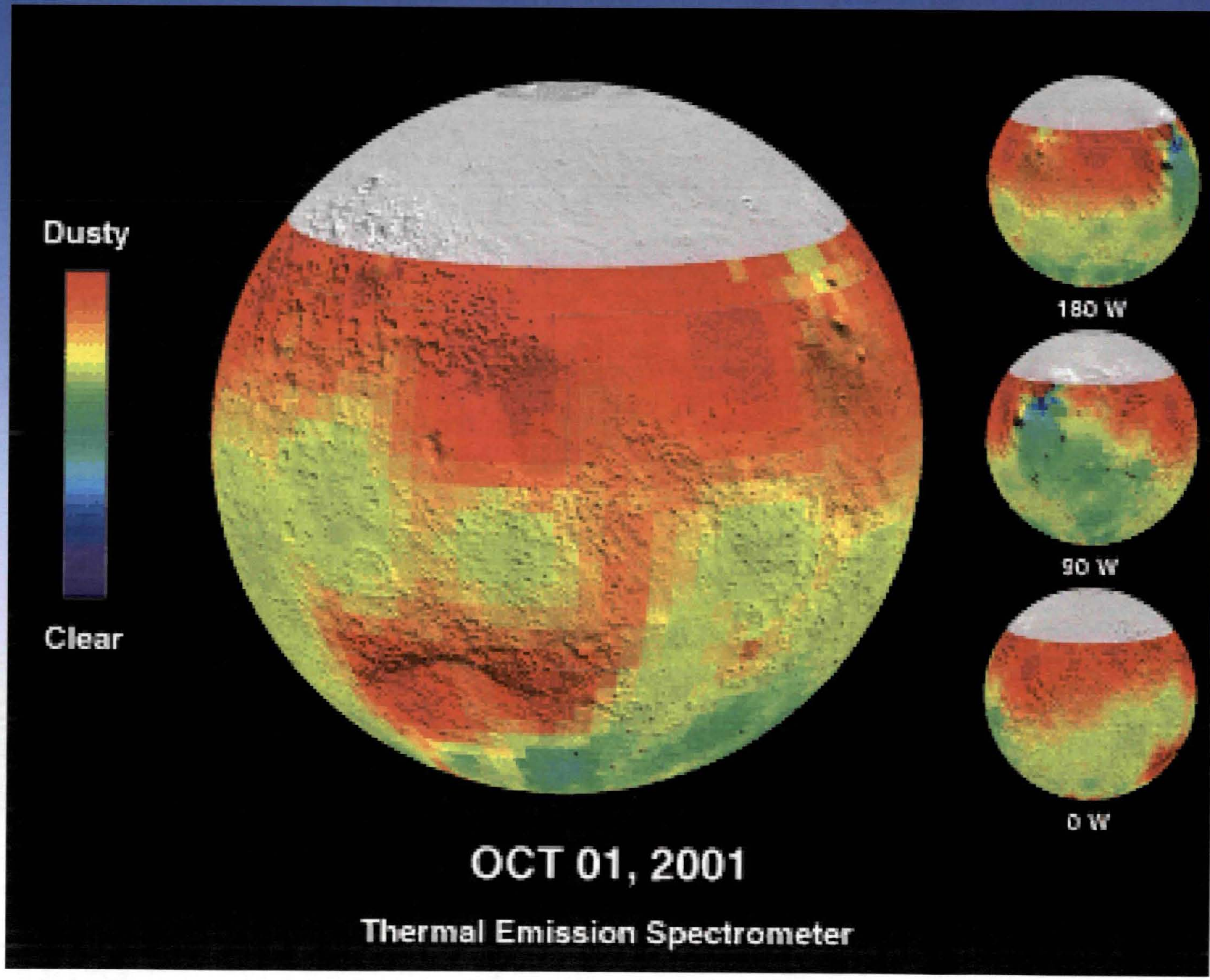

Martian dust devils

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Martian dust devils

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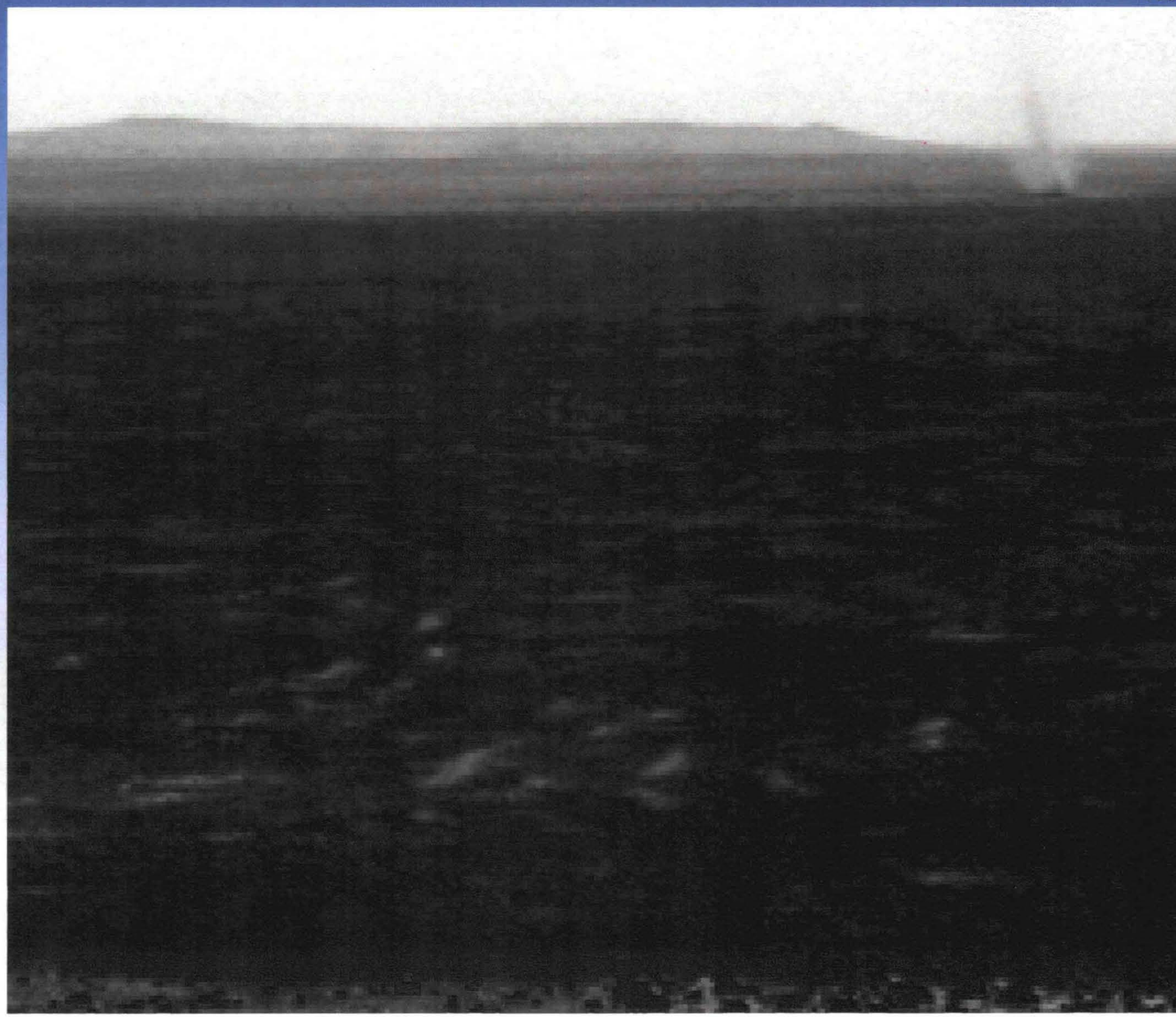

Electrodynamic dust shield

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- NASA KSC's Electrodynamic Dust Shield Technology removes dust from optical systems and prevents dust accumulation
- Dust Shield is based on the Electric Curtain concept developed at NASA in 1967
- Masuda at U. Tokyo built first prototypes (1970s)
- NASA KSC and University of Arkansas developed EDS for Mars
  (NASA Science Mission Directorate NRA - 2003-2006)
- KSC currently developing technology for lunar applications (ESMD Dust Project)

Controlled dust motion

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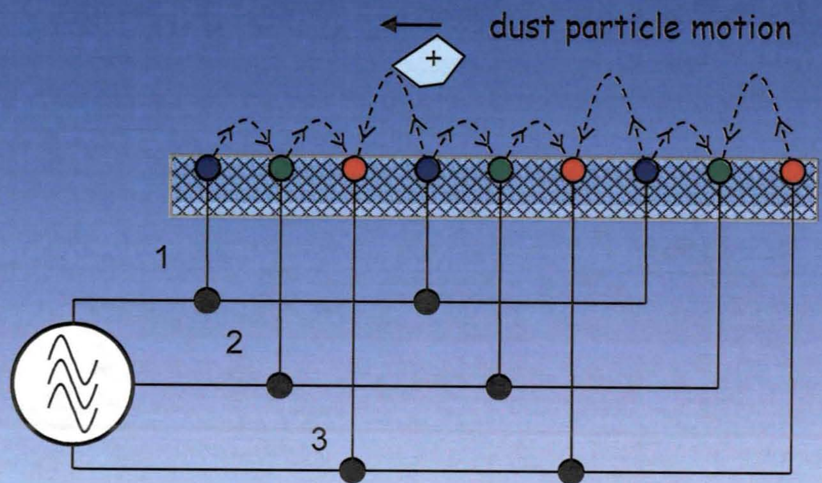

Three-phase electrode pattern with **phase 1** electrodes at V_1=-V, **phase 2** electrodes at V_2=+V, and **phase 3** electrodes at V_3= +V. Charged particles will move in a particular direction.

Three-phase dust shield with indium tin oxide transparent electrodes in a spiral pattern configuration on a glass substrate

Transparent Dust Shields

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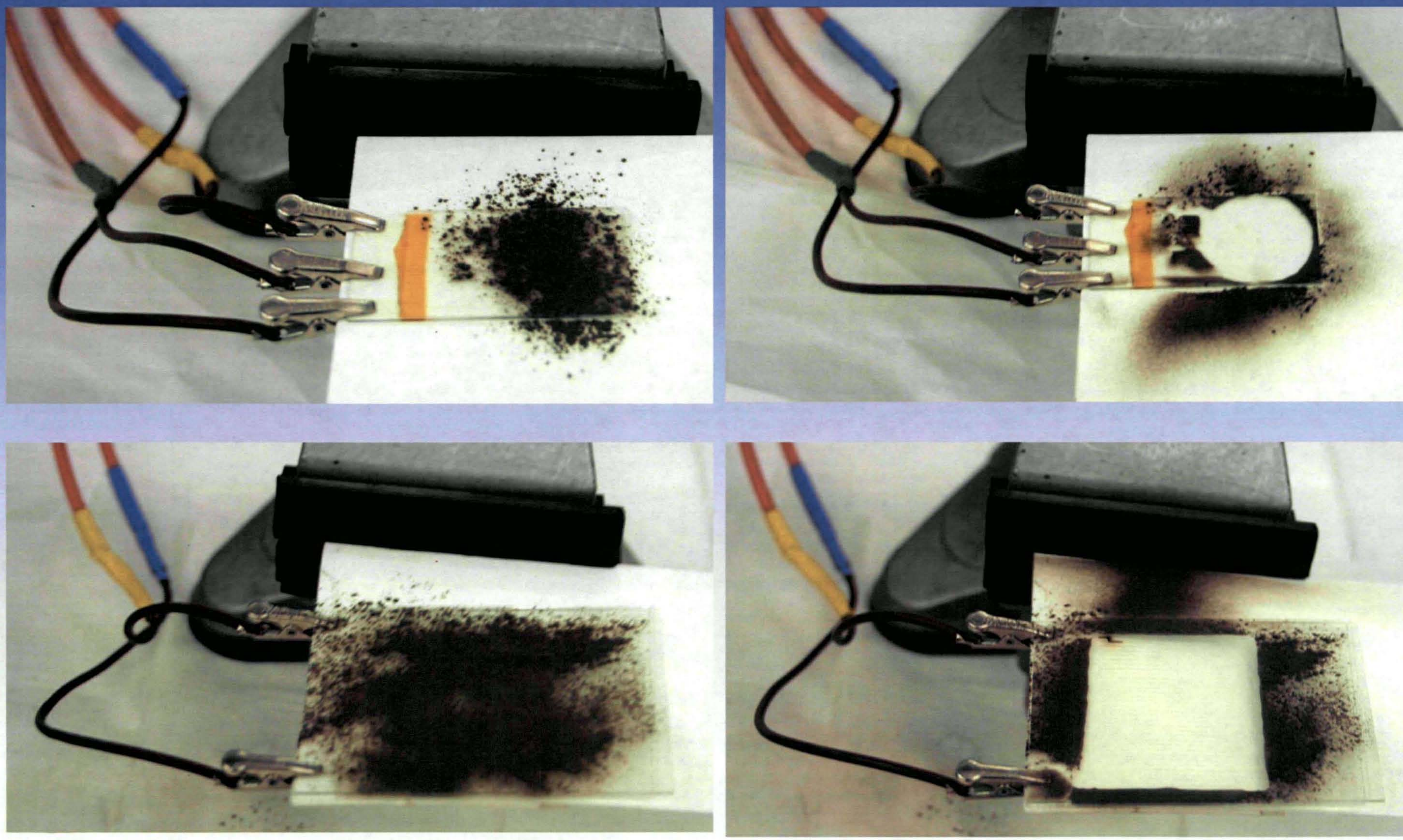

Electrodynamic dust shield

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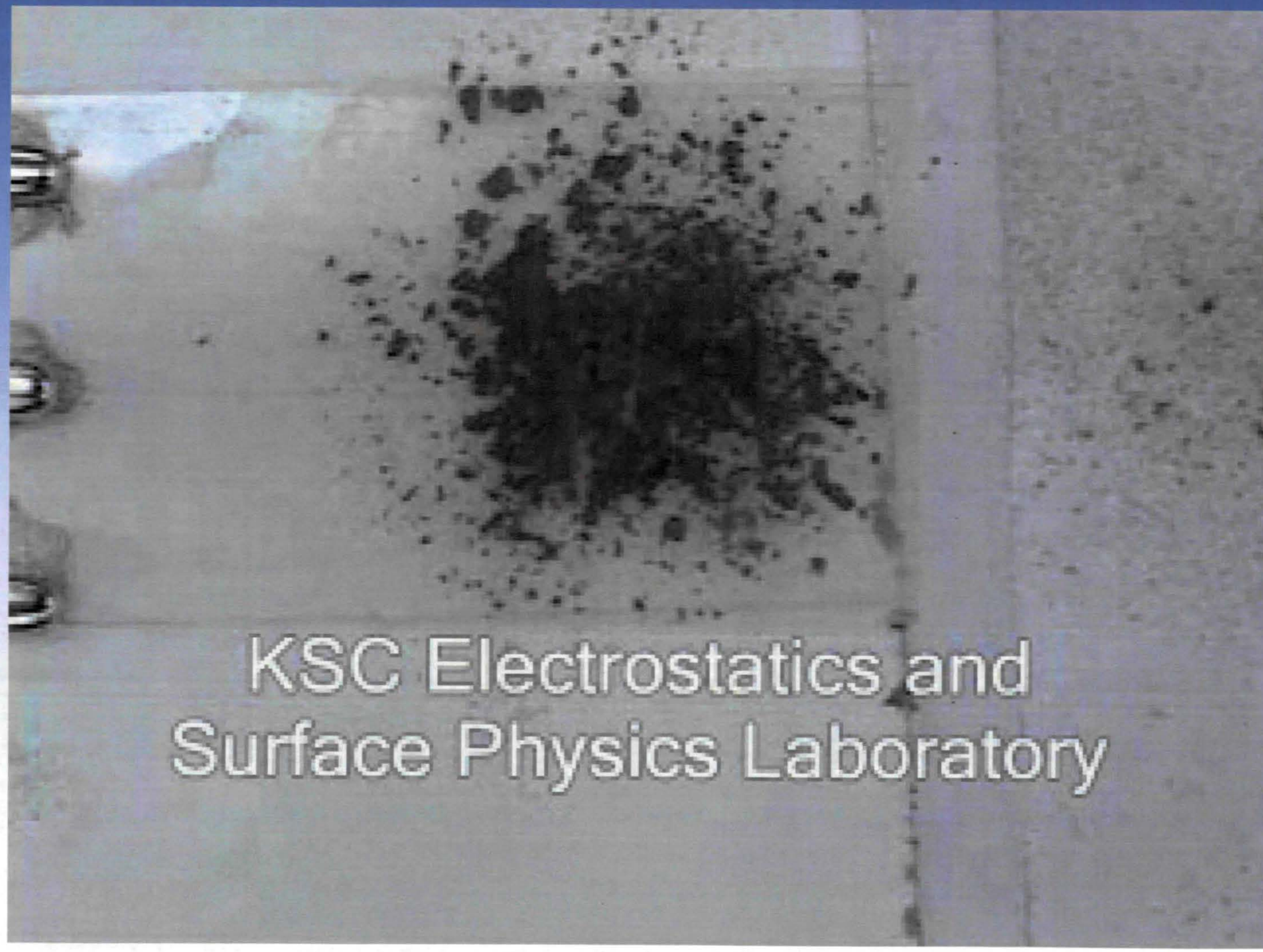
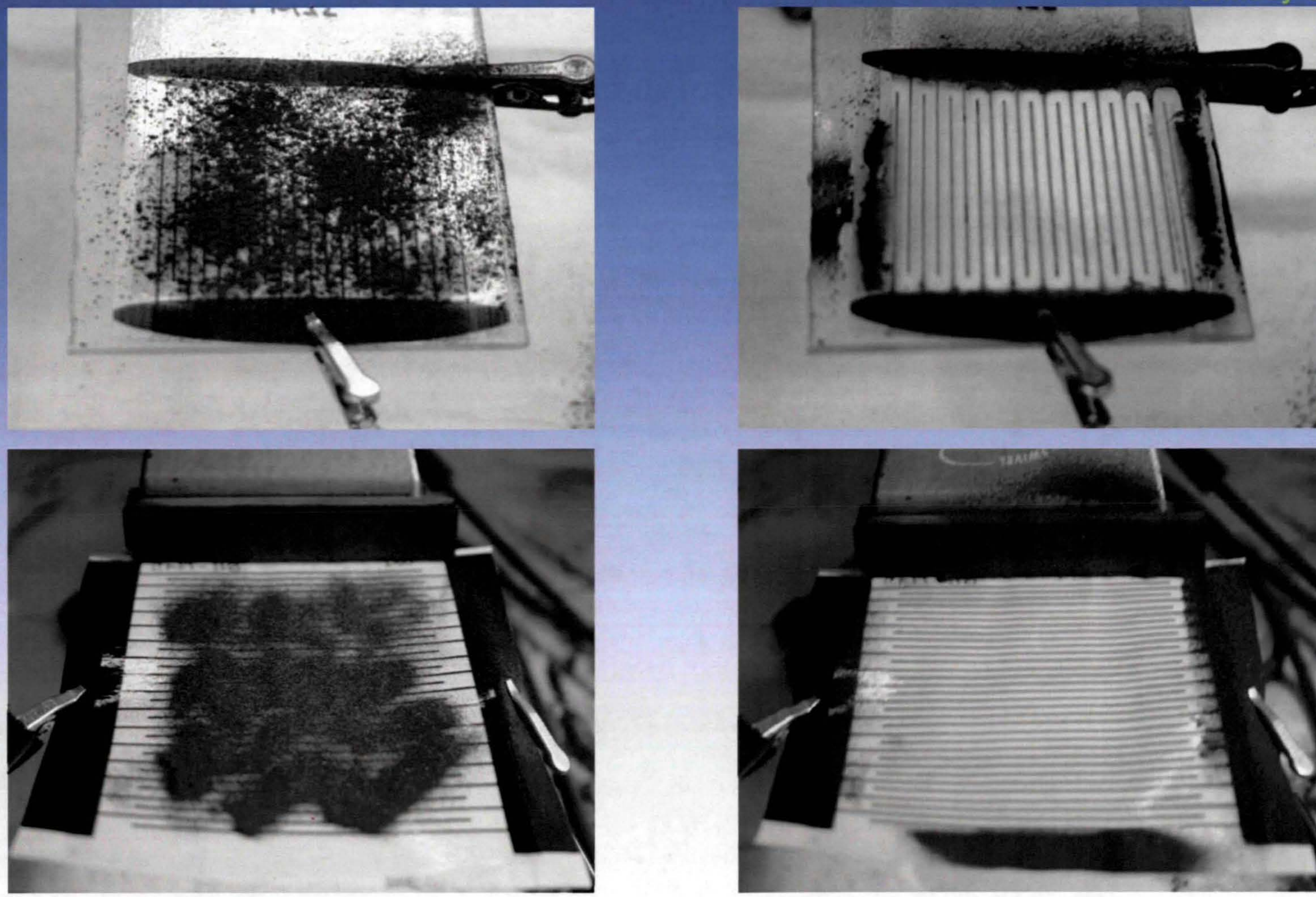


Flexible Dust Shield on Fabric

Kennedy Space Center



- Before and after photographs of a dust shield on fabric with JSC-1A, 50-75 µm lunar simulant in air

Purpose of Experiment

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- Demonstration of Electrodynamic Dust Shield at
  - High vacuum
  - Lunar gravity on Reduced Gravity Flight
    - Over 120 experiments
      - JSC 1A simulant
      - Apollo 16 samples
- Used LaRC vacuum chamber

Reduced Gravity Experiments

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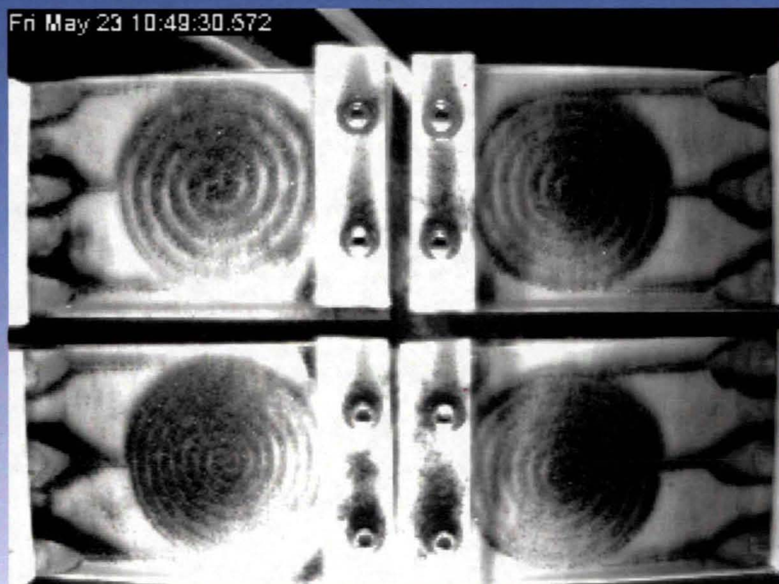

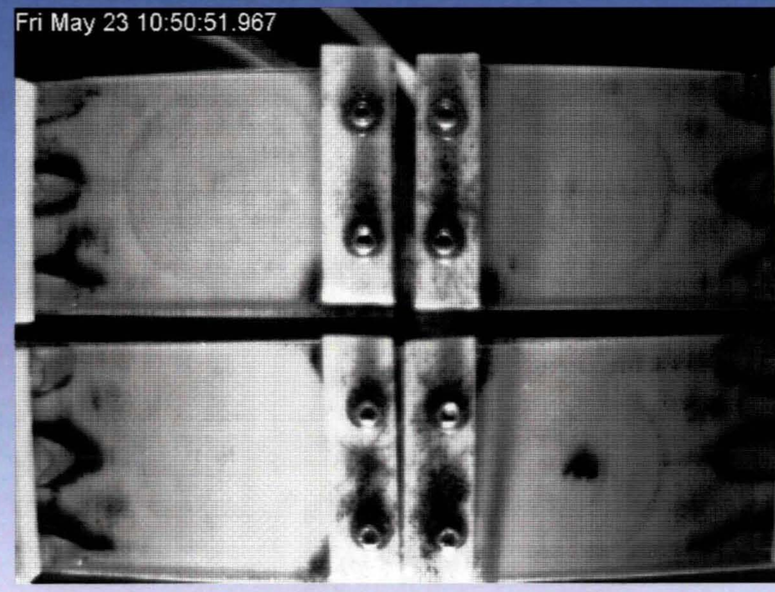

- Before and after stills of four transparent dust shields in one of the boxes used in RGF 1. Sample size: 50-100 μm

Removal of JSC-1A (<10μm)

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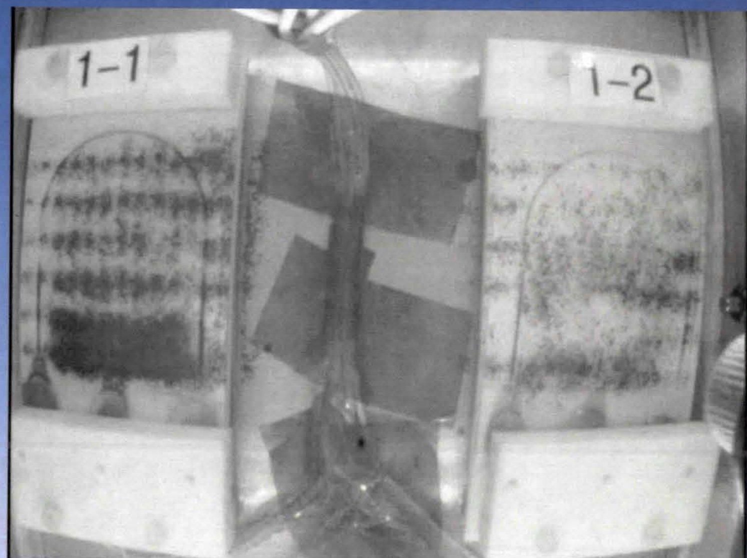

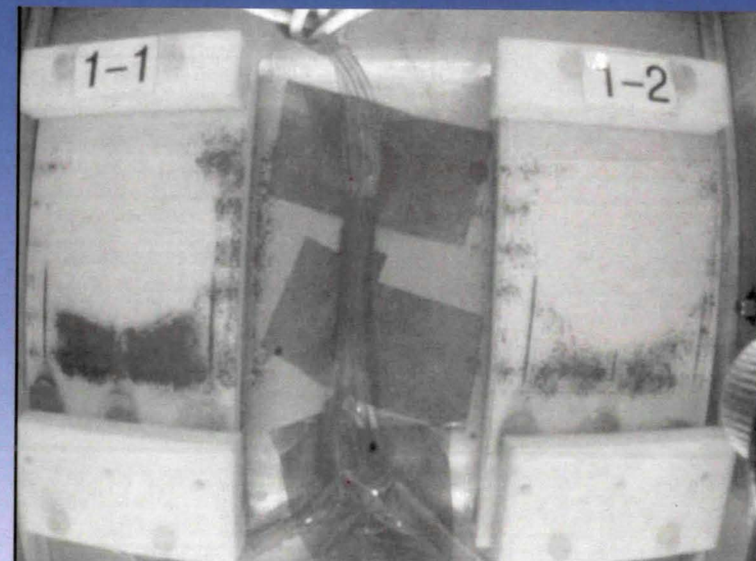

- Before and after stills of one of the boxes with JSC-1A (<10 μm fraction)
- Experiment performed during RGF 2 at $^1/_6$ g and at 10^{-6} kPa

Removal of Apollo 16 Sample

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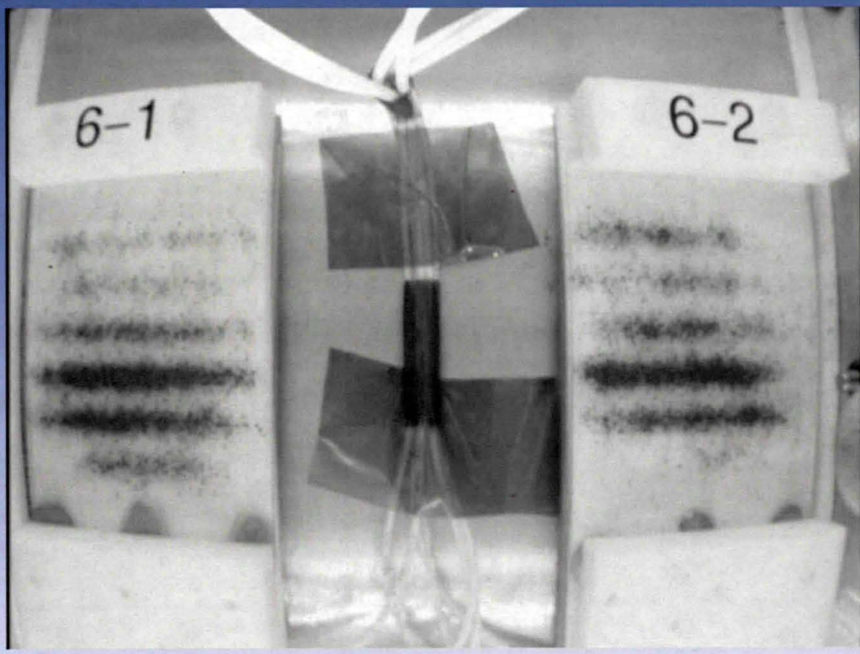

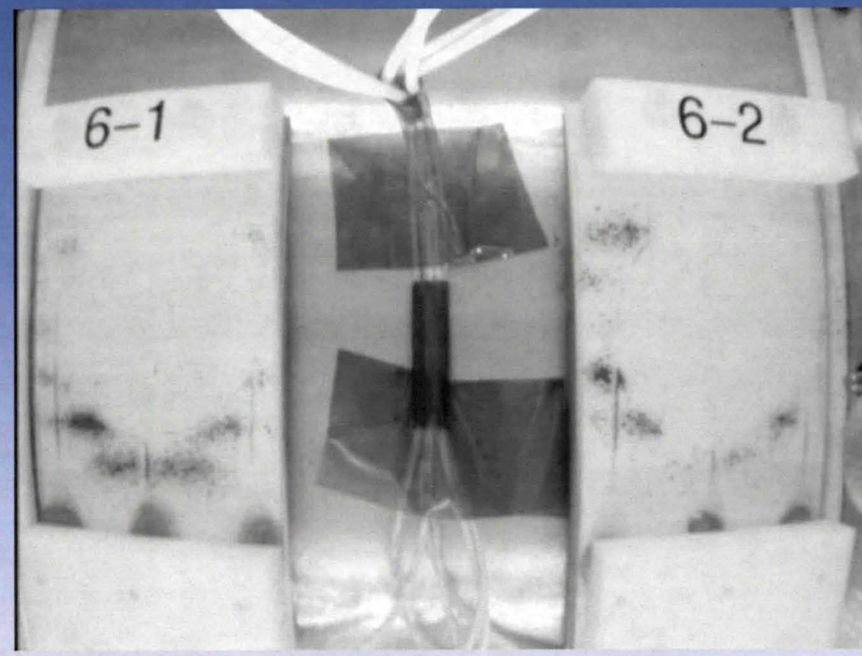

- Before and after stills of Apollo 16 sample removal
- Experiment performed at $^1/_6$ *g* and at 10^{-6} kPa

RGF flights

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EDS for RESOLVE

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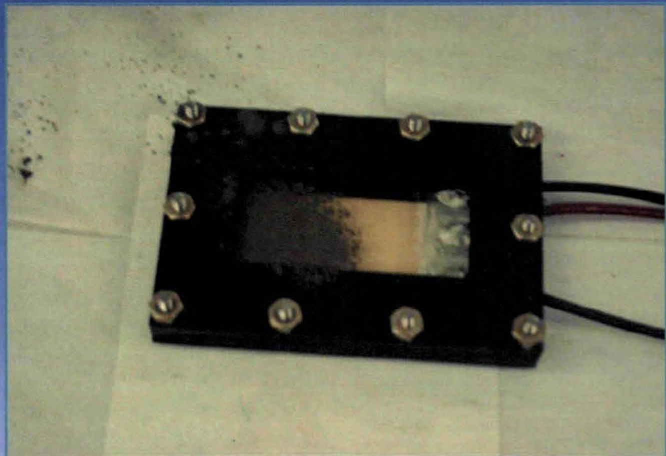
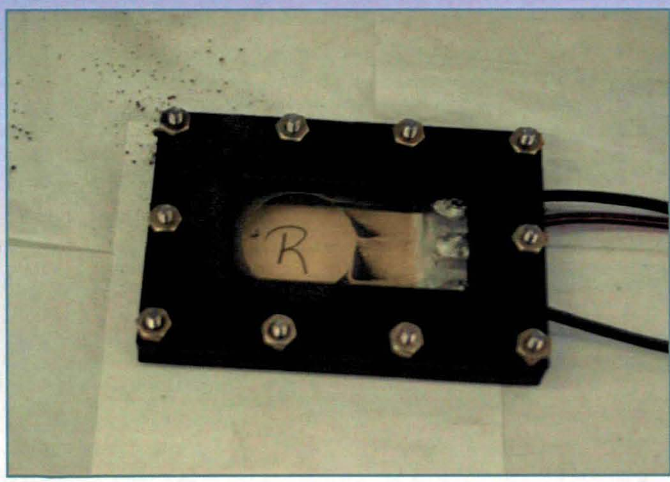
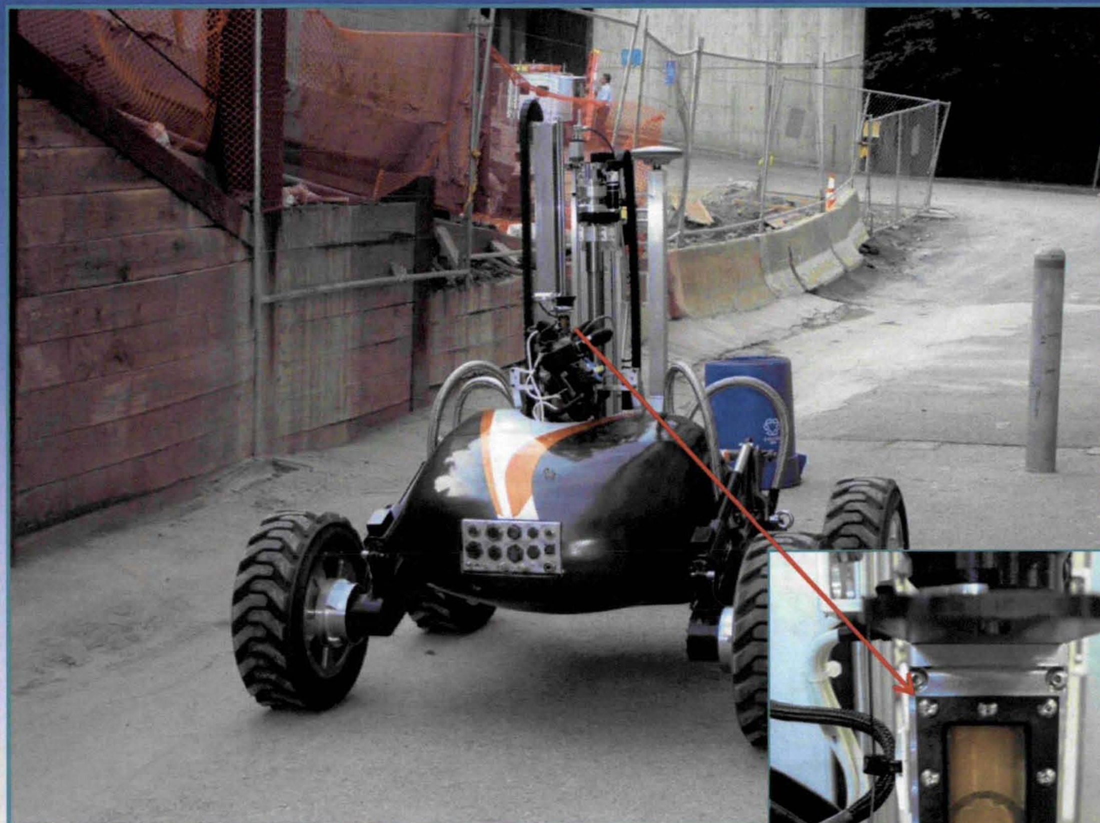
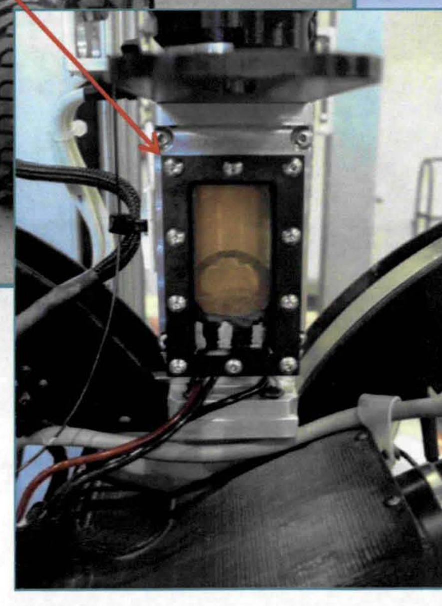




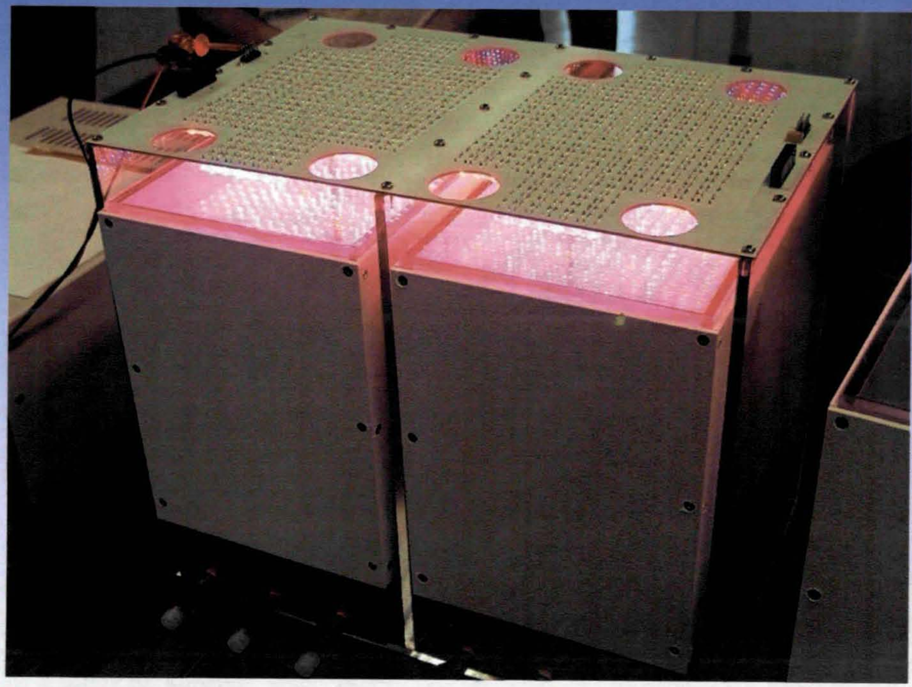


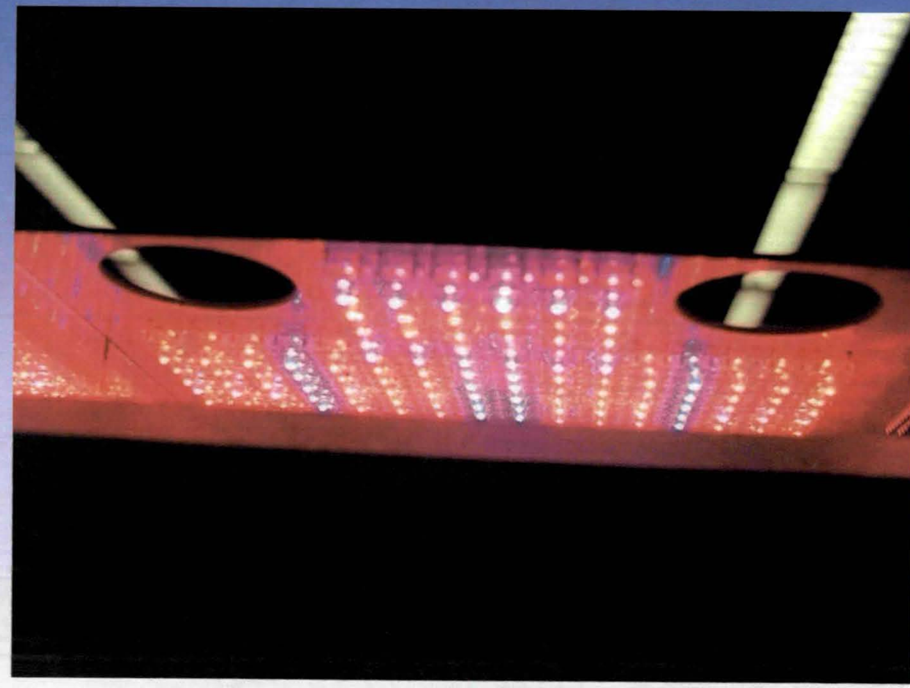


Spiral EDS mounted on RESOLVE rover

Space food

Kennedy Space Center





Plants growing under red and blue LEDs

Plants for space habitats

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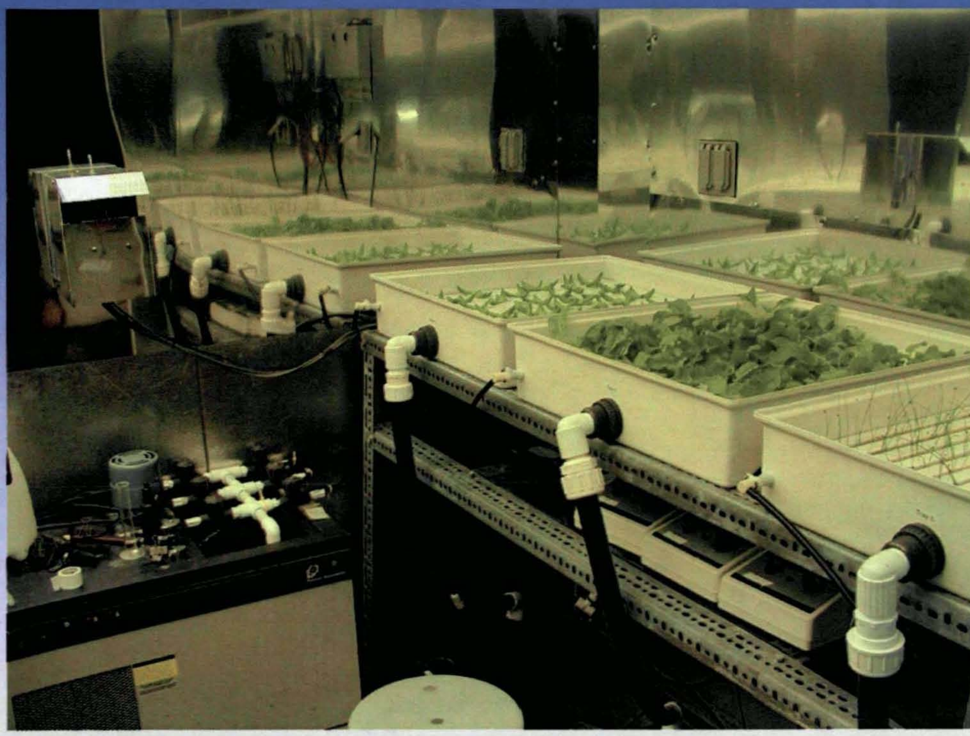
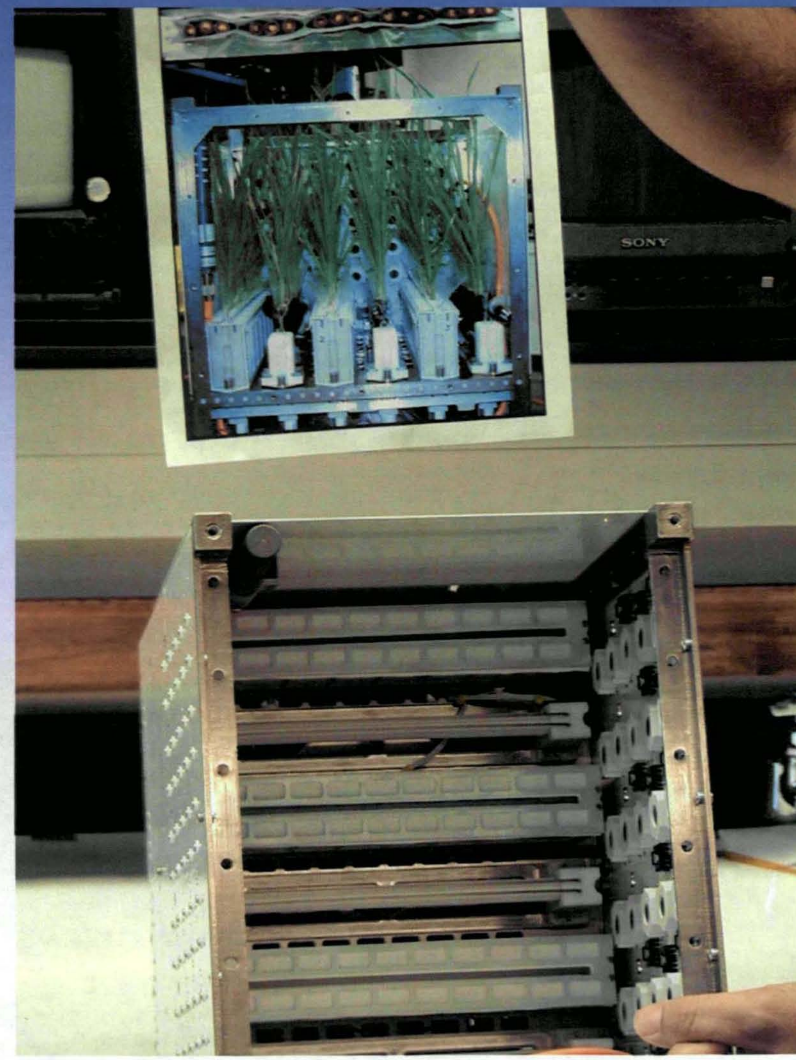
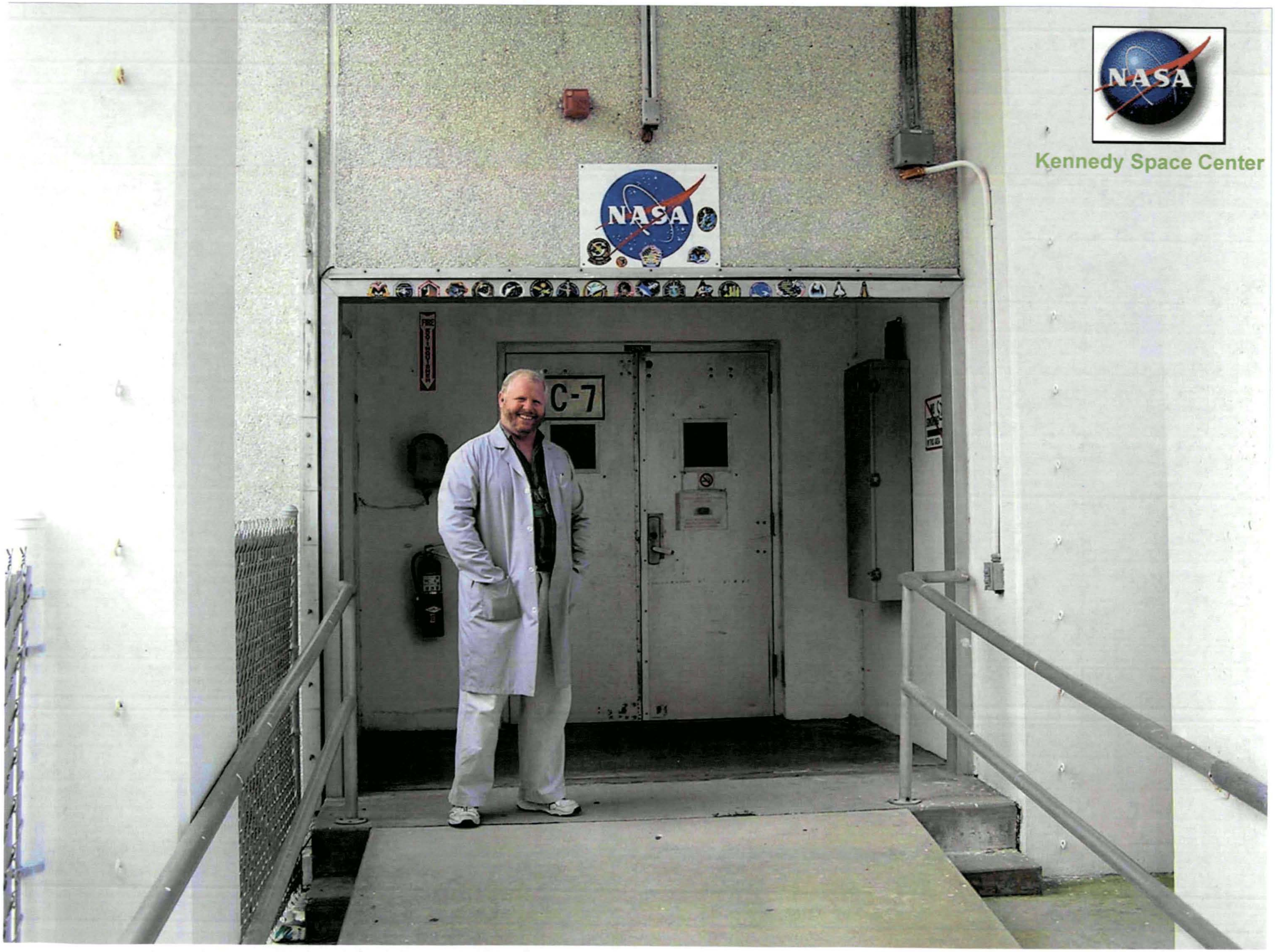




Plants growing under various environments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NASA
AIRSTREAM


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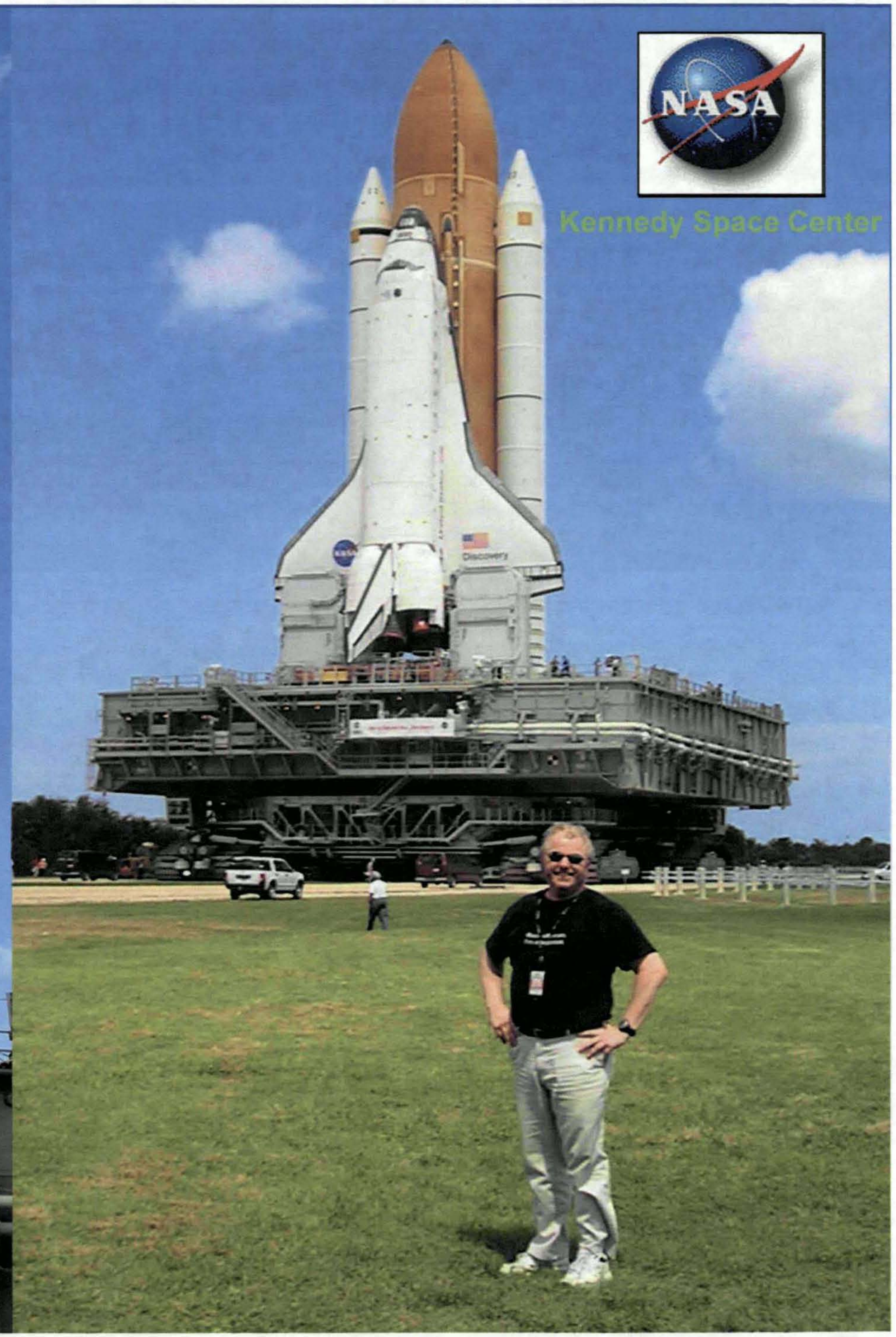
We're Behind You, Discovery!
USA
United Space Alliance
STS-114


NASA
Kennedy Space Center
1
SIDE 3
1


United States
Discovery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Discovery


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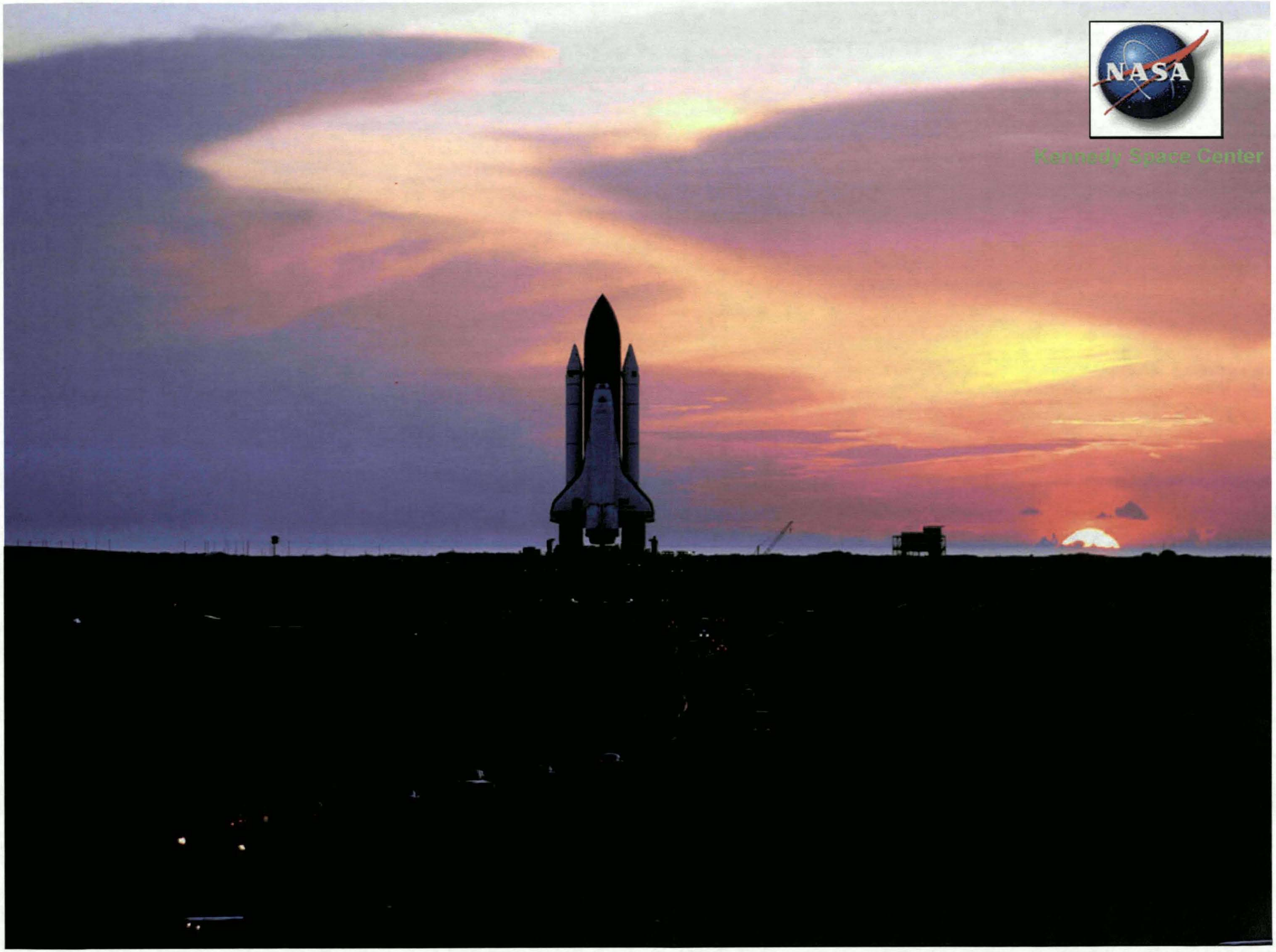
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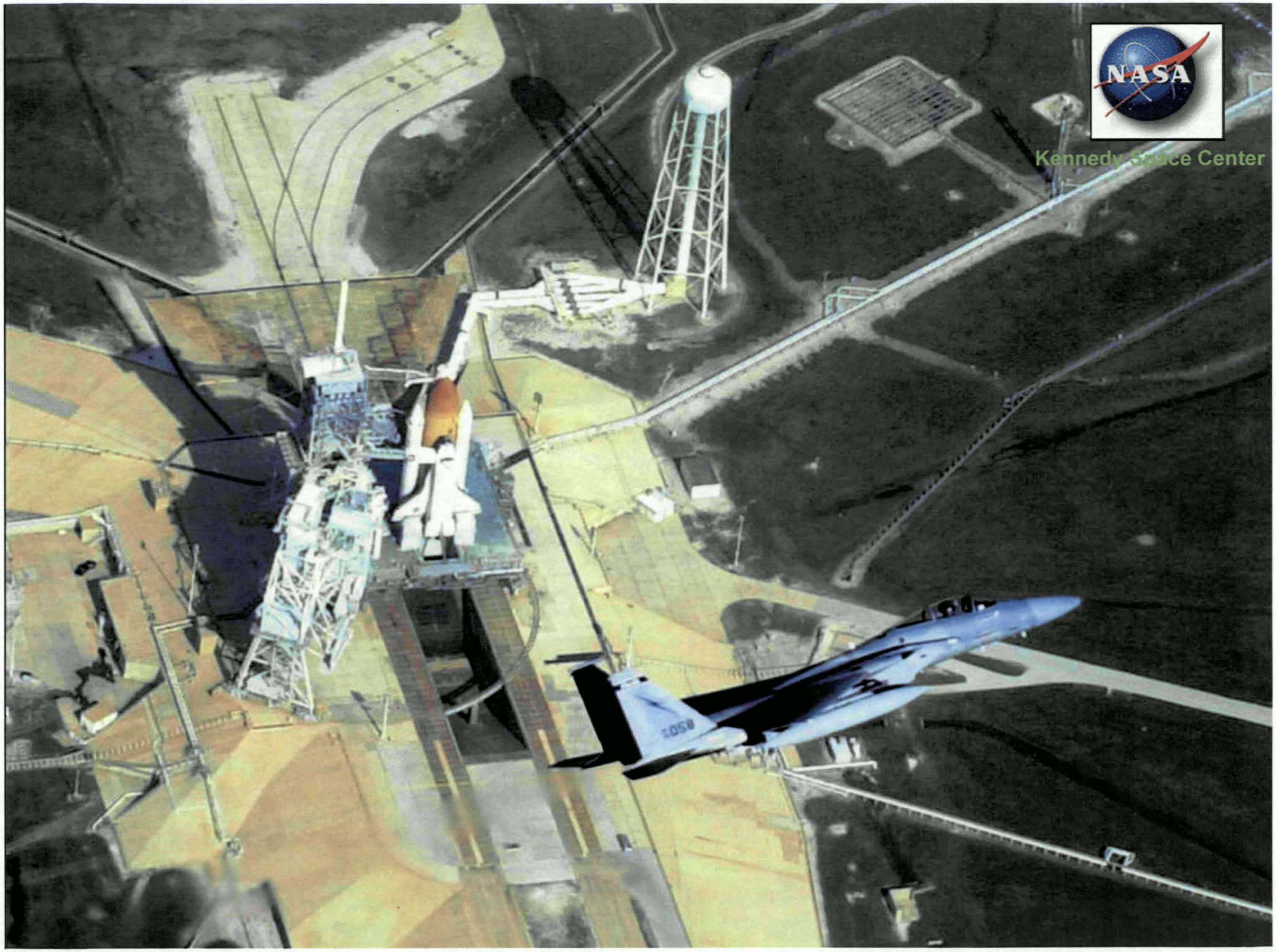

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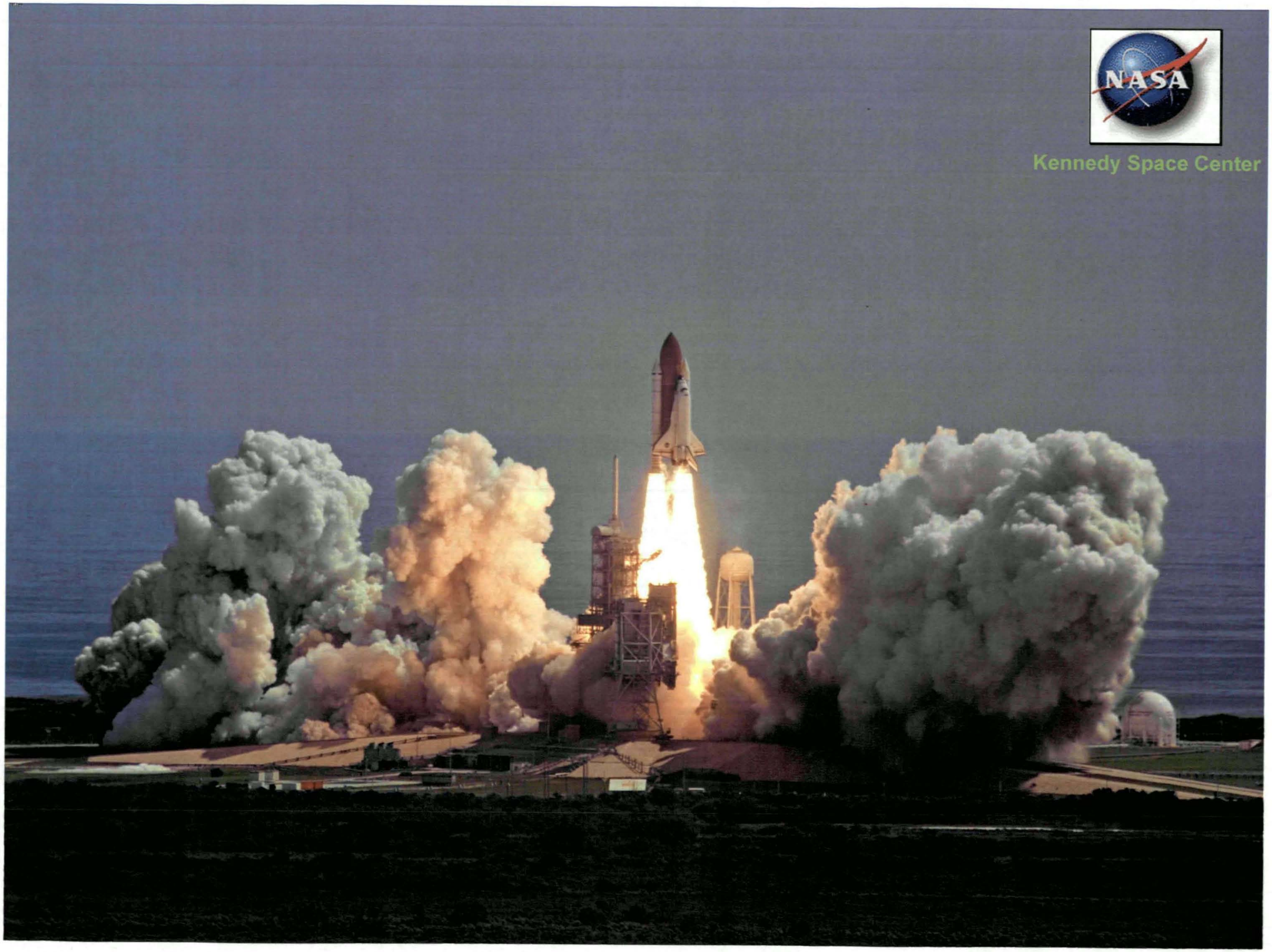
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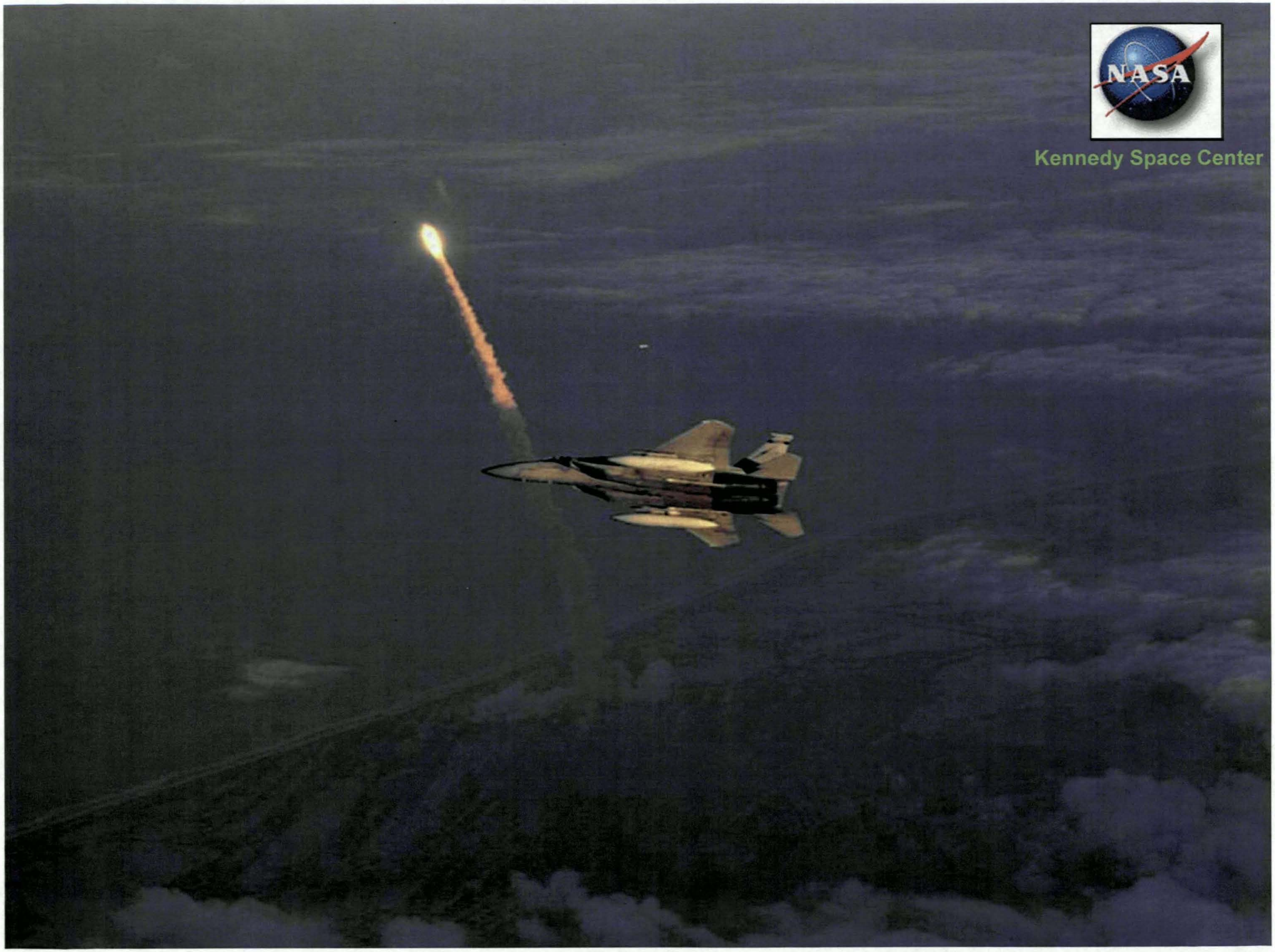
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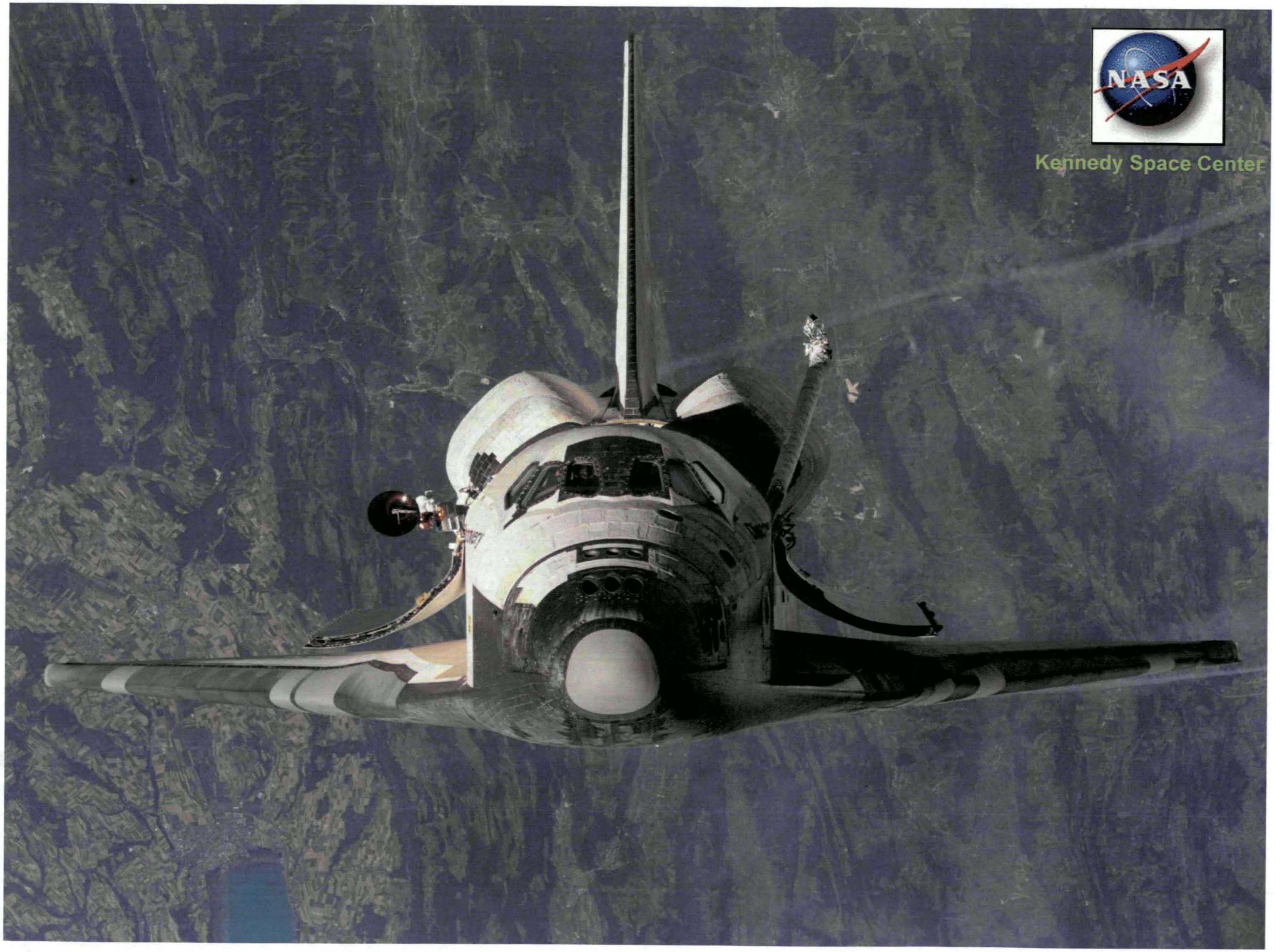
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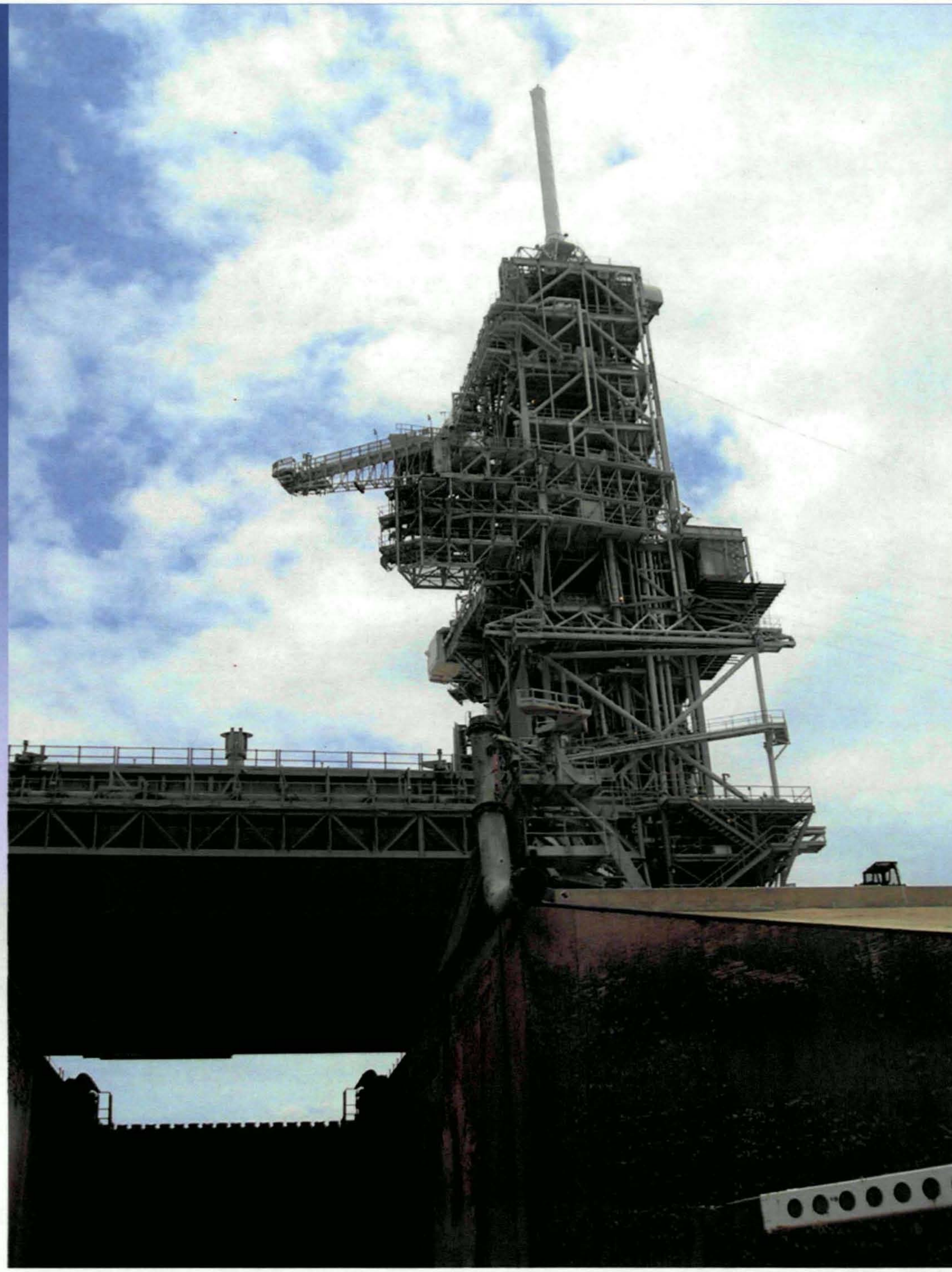

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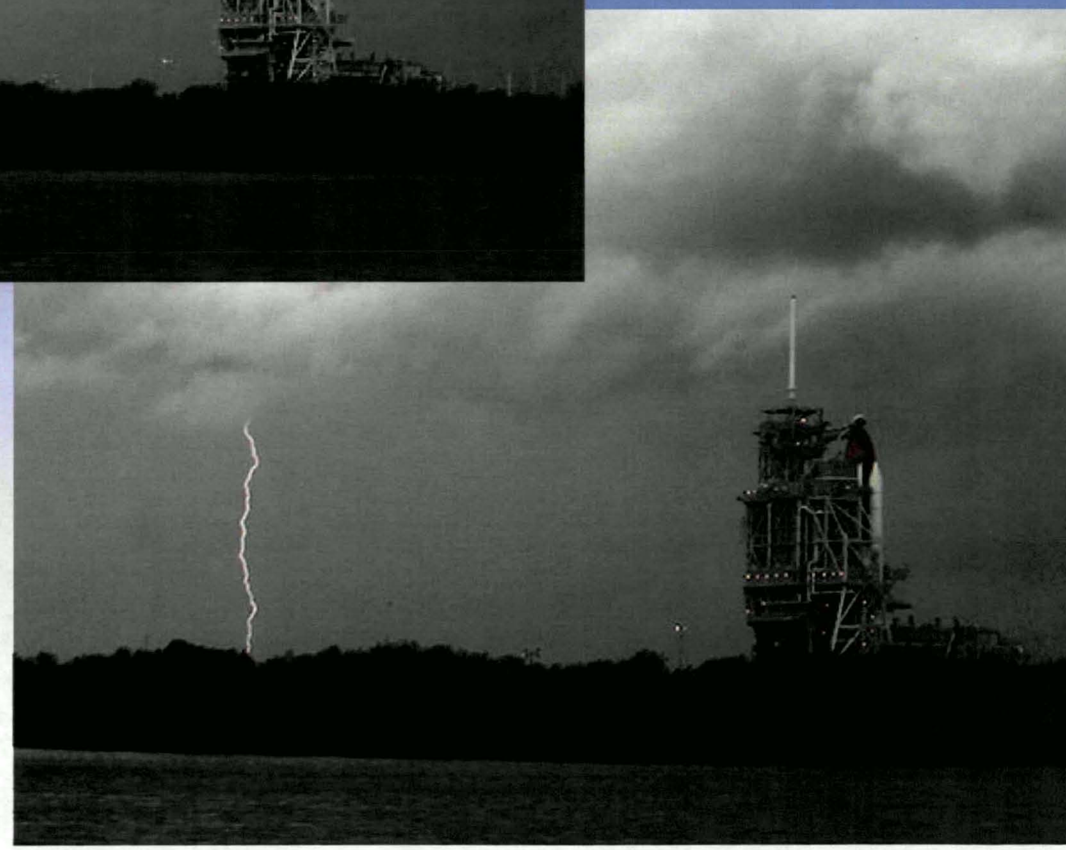

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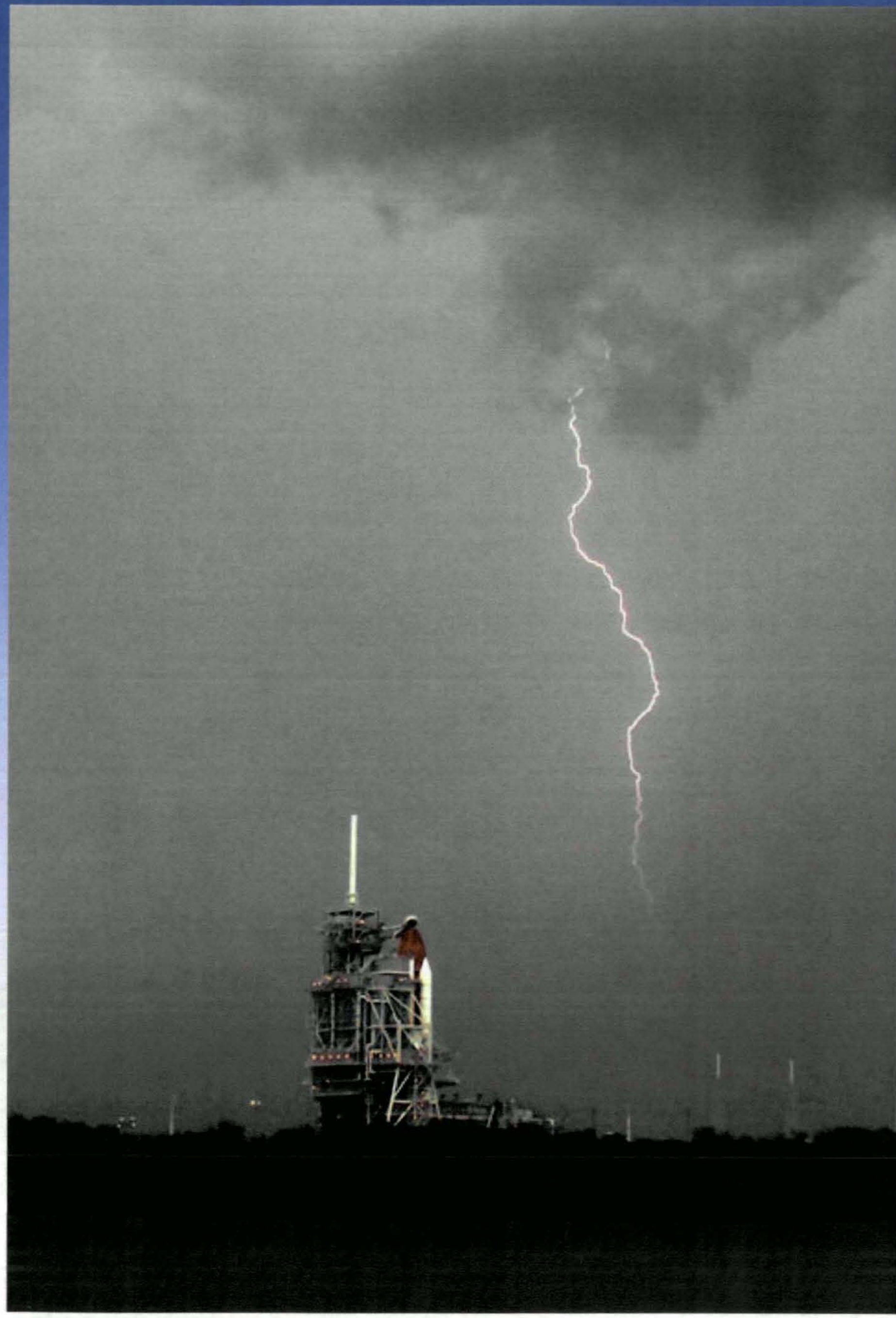

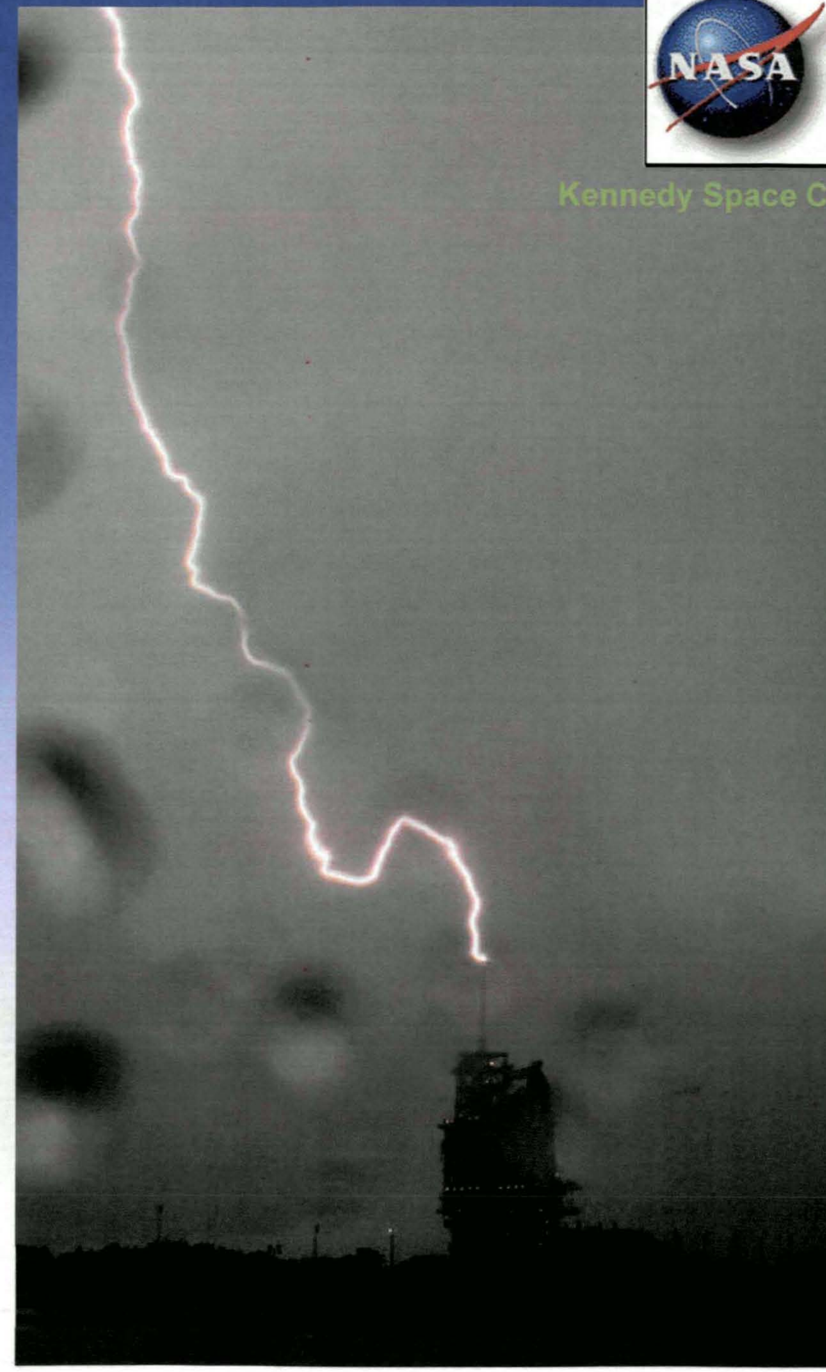

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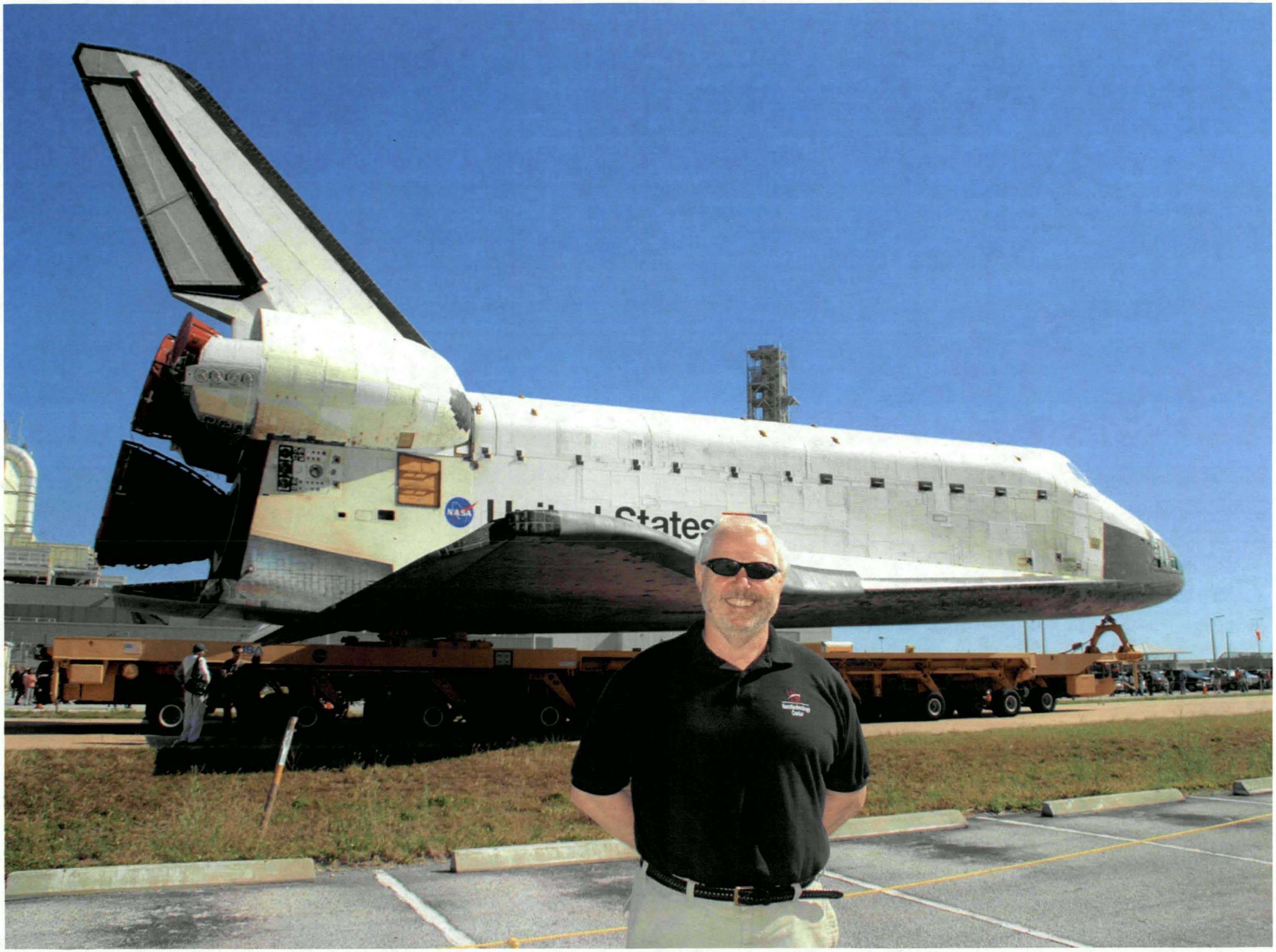
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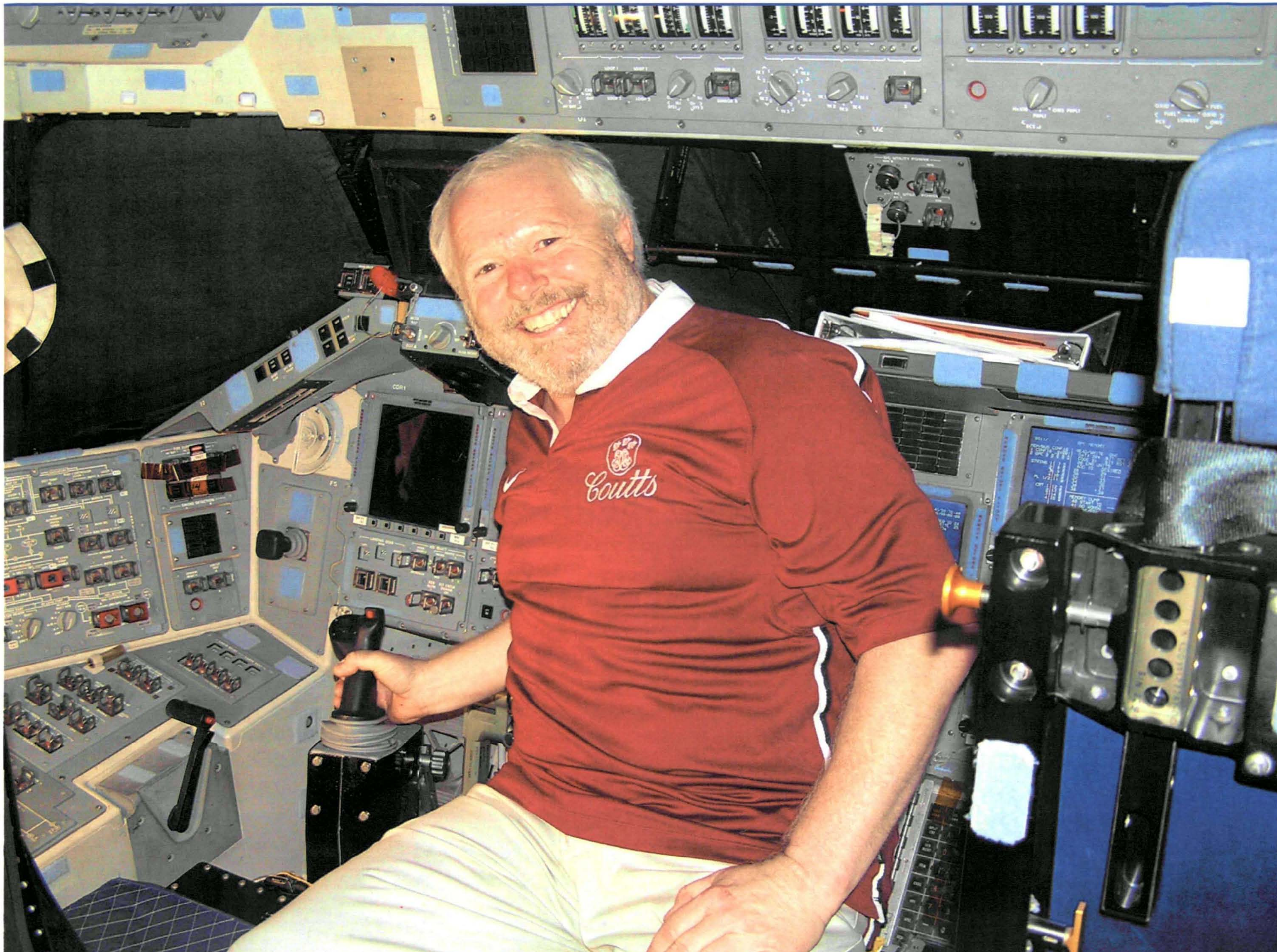
Coutts

LAMP TEST
X-PNTR SCALE
X1
X10
RANGE RATE/AZIMUTH
W10
CAMERA POWER
TV POWER
CONTROL CONTR UNIT
BRAKES
SAFING
SOFTWARE STOP
MODE
Coutts
BACKUP CONTROL
JOINT
SHOULDER
ELBOW
WRIST
PITCH
YAW
PAYLOAD RELEASE
DIRECT DRIVE
WIRELESS VIDEO
POWER
PORT
FWD BHD